Integrated InP Arbitrary Waveform Generation and Detection for THz Advanced Format Trx and Rcv

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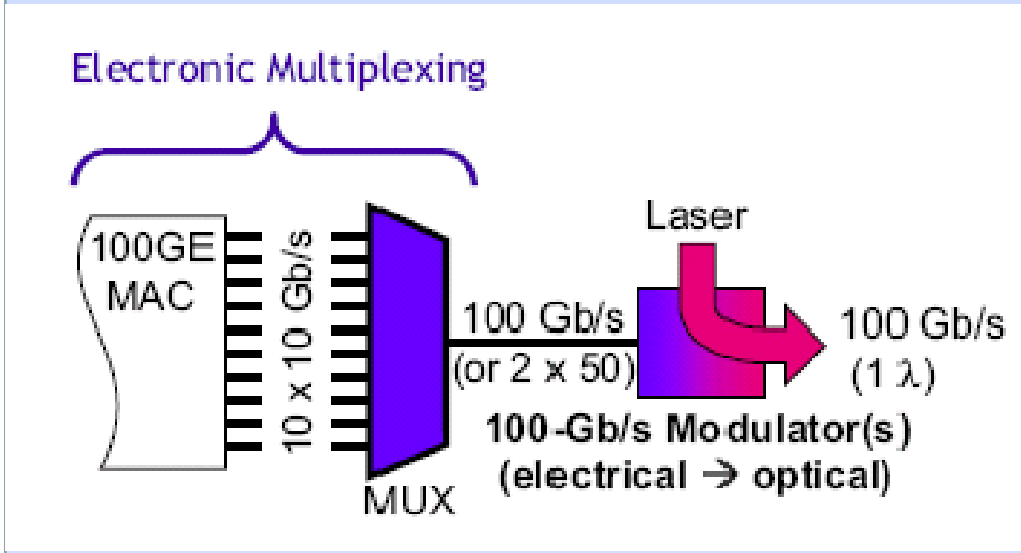
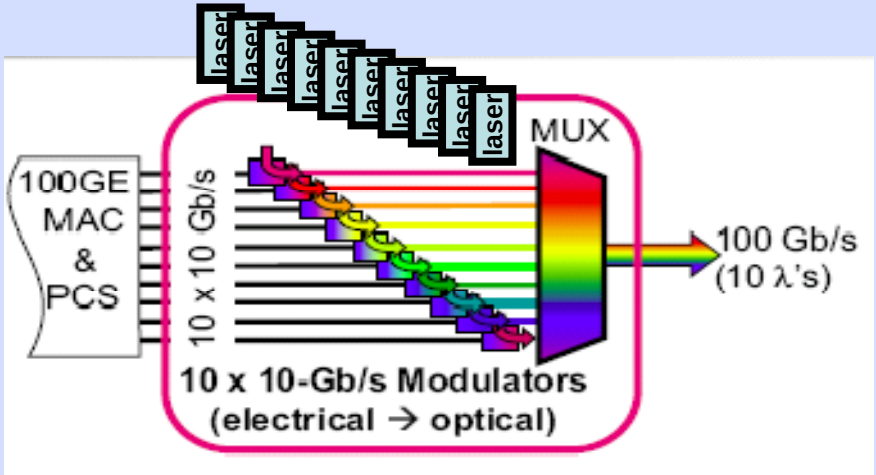
Serial vs. Parallel 100 G technology

100G serial transport



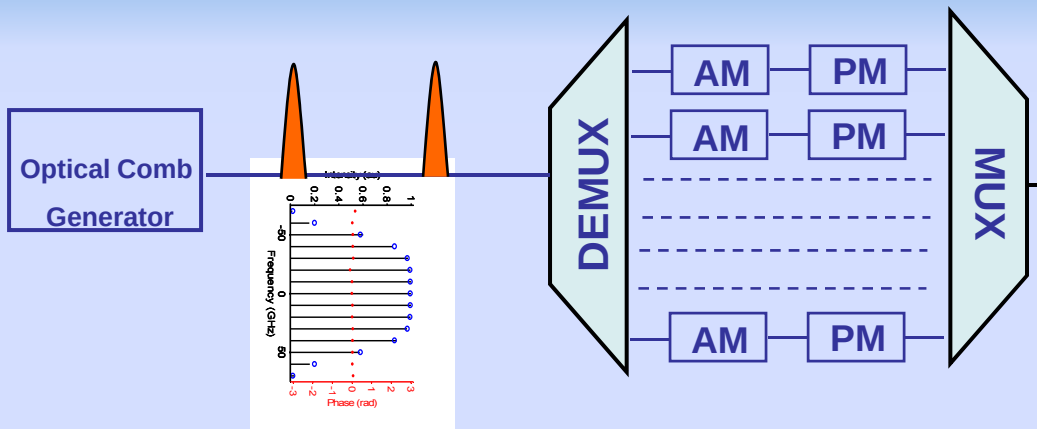
100G parallel transport (OTN VCAT)

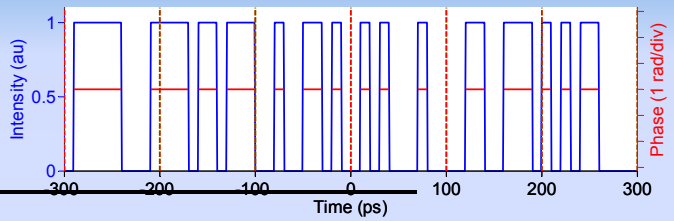


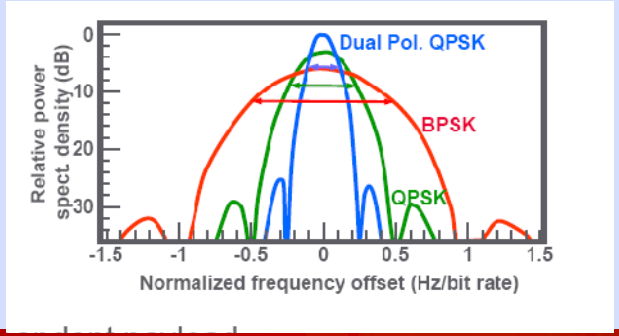
- Use *single* wavelength (can be *multi-level*)
- Needs 100 G (or 2x50G) electronics
- Better spectral efficiency but more sensitive to dispersion and PMD

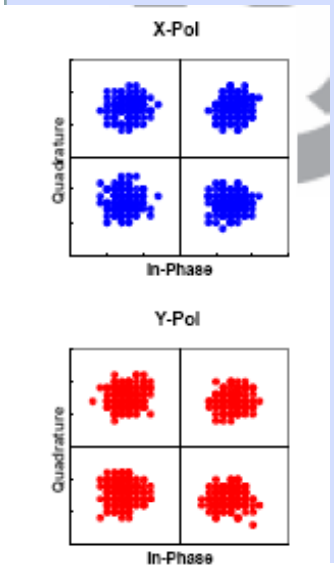
- Use *multiple* wavelengths & modulators
- Needs 10 G electronics with possible synchronization
- Manageable dispersion and PMD but poorer spectral efficiency

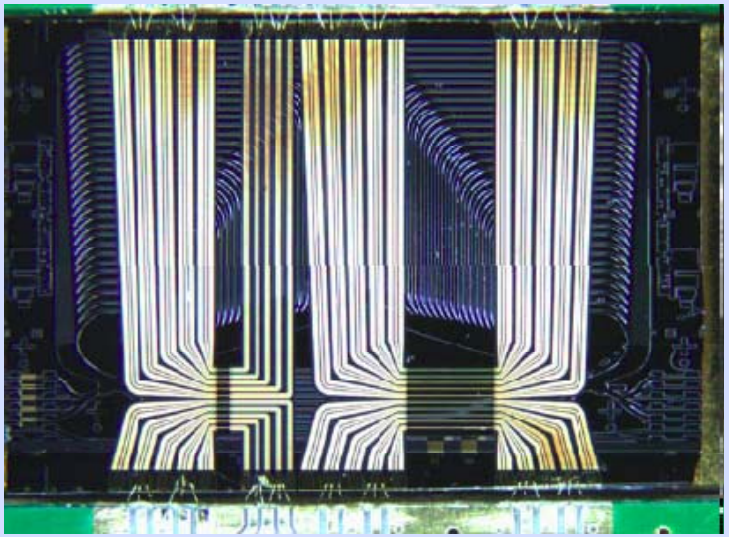
Scalable Optical Arbitrary Waveform Generation

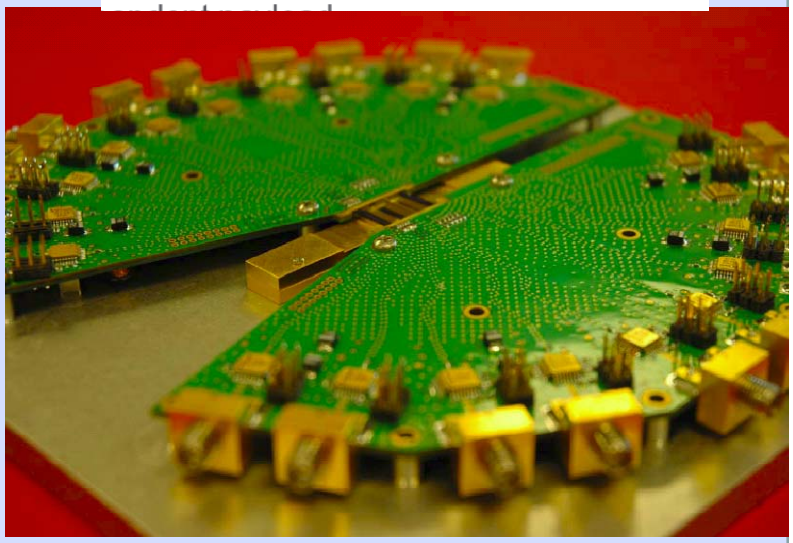












- At a glance, this is useful for parallel 40G/100G Trx/Rcv with independent ASK, PSK, DPSK, QPSK, DQPSK, etc.

Optical Arbitrary Waveform Generation

Parallel GHz Rate Intensity and Phase Modulation

Bandwidth-Scalable

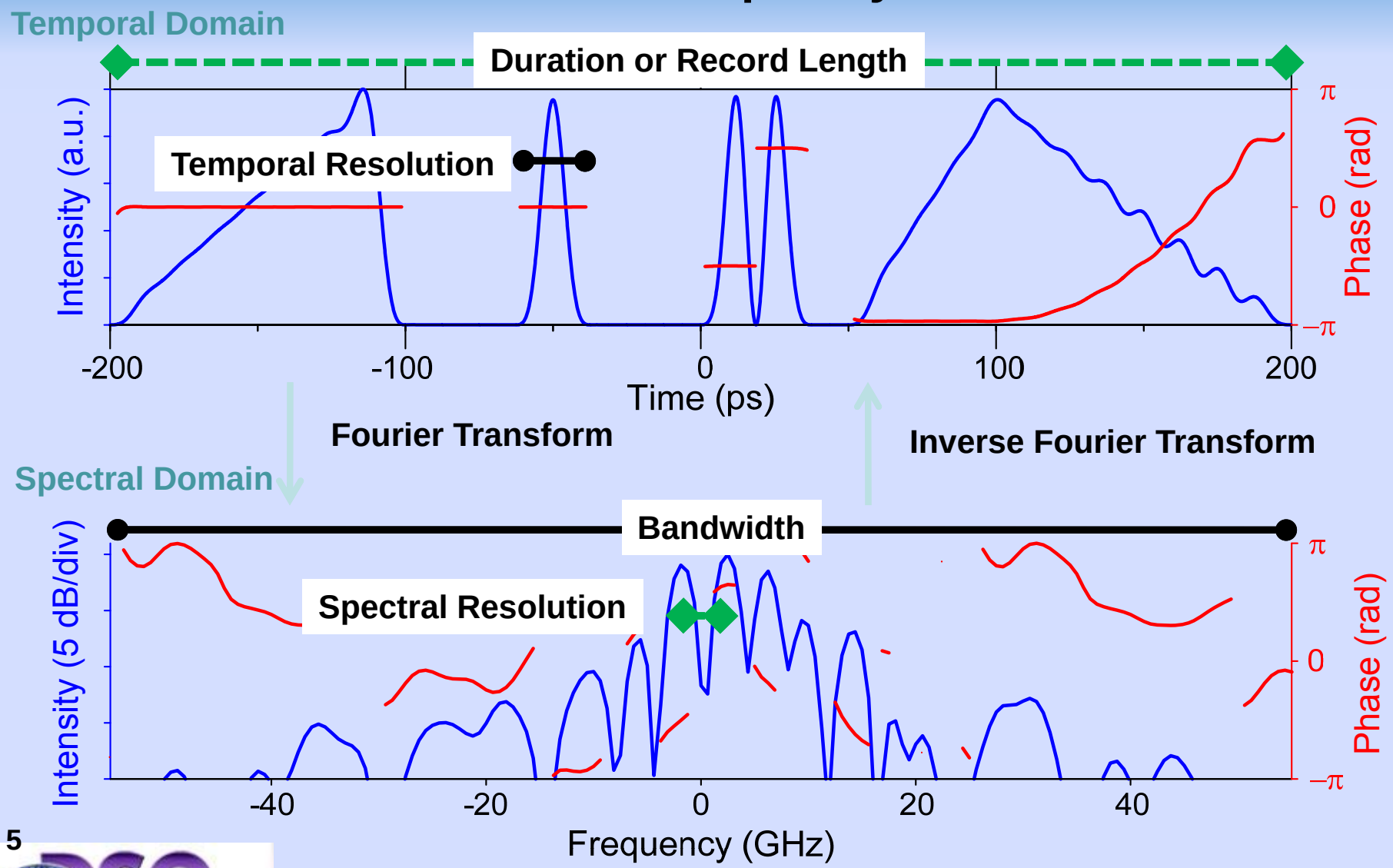
THz Rate Optical Arbitrary Waveform

Spectral Demultiplexer

Spectral Multiplexer

- **Fourier Synthesis of Arbitrary Waveforms scaling to Terahertz BW**
- **Optical arbitrary waveform generation with high-speed modulation**
- **Tradeoff between wide-optical-bandwidth and electrical-bandwidth**
- **High-resolution AWGs can offer high-capacity signal processing systems based on low bandwidth electronics (< 10GHz)**
- **Monolithic InP construction in support of high-speed modulation**

Optical Arbitrary Waveform Generation
Time/Frequency



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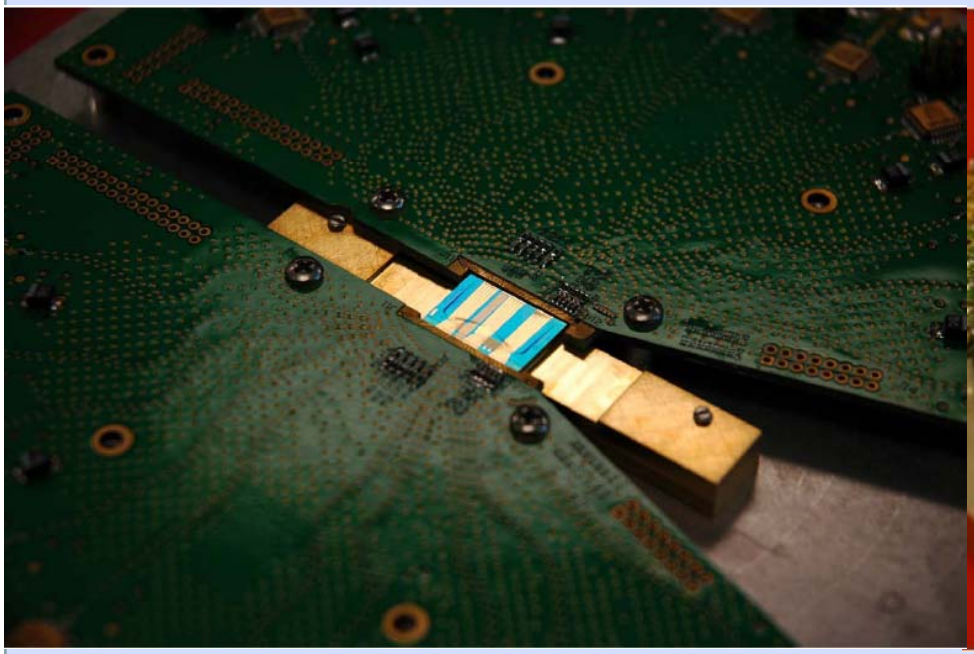
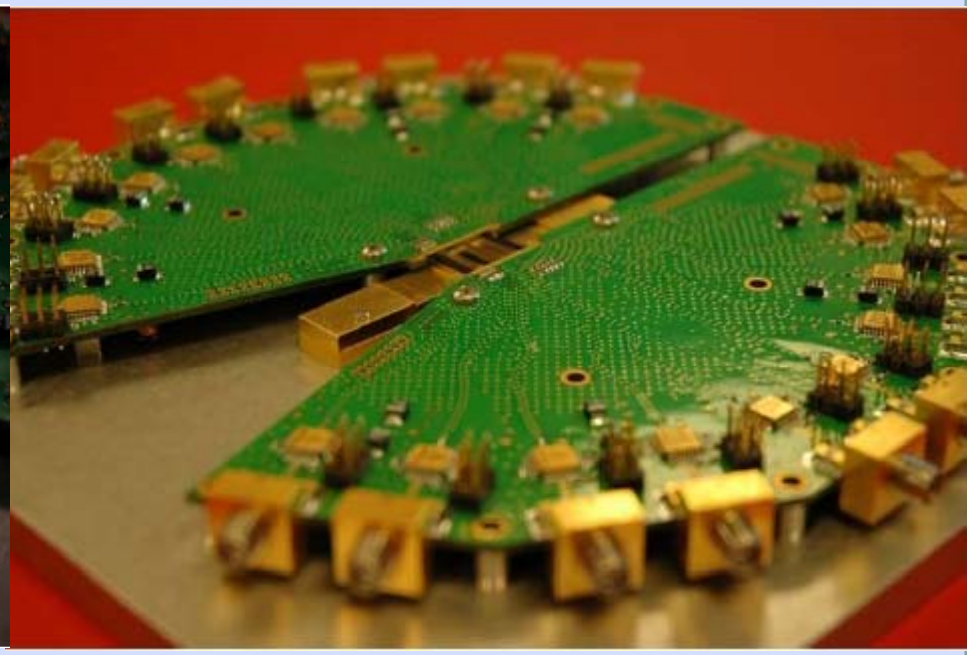
Packaged InP OAWG
(10 Ch AM+ 10 Ch PM) x 10 GHz
AM-PM modulation board





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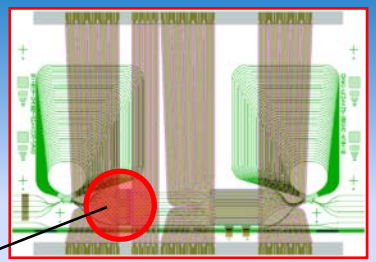
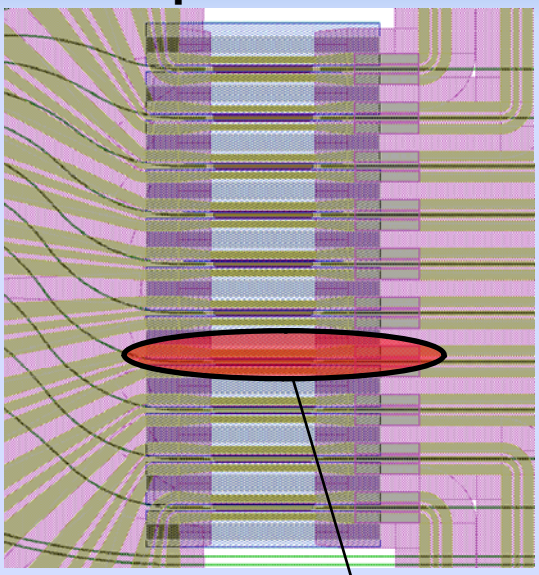
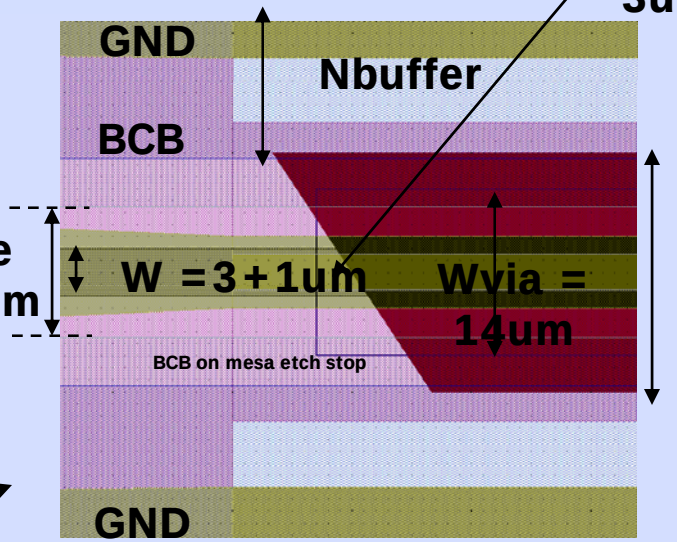
OAWG: TW-EA

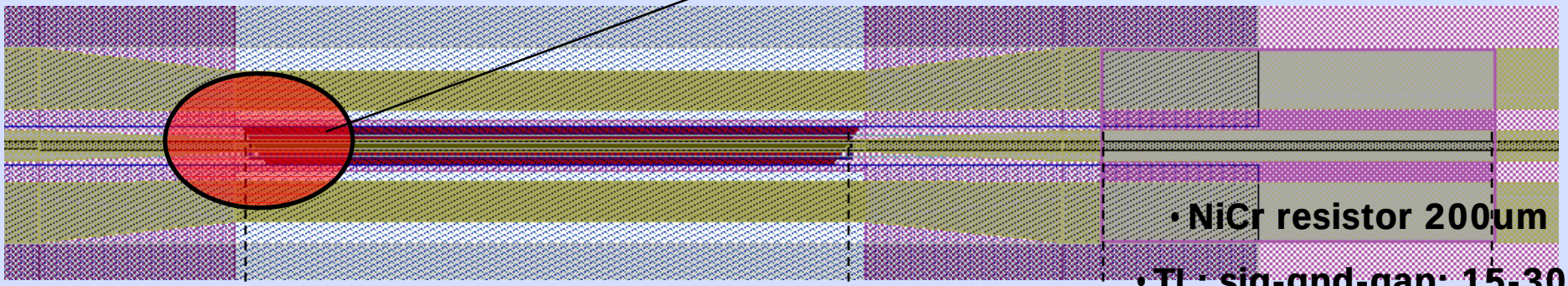


EA pitch=150um



BCB opening = 3um





- NiCr resistor 200um
- TL: sig-gnd-gap: 15-30-11.5um
- EA Length = 300um
- TL: sig-gnd-gap: 6-20-15um

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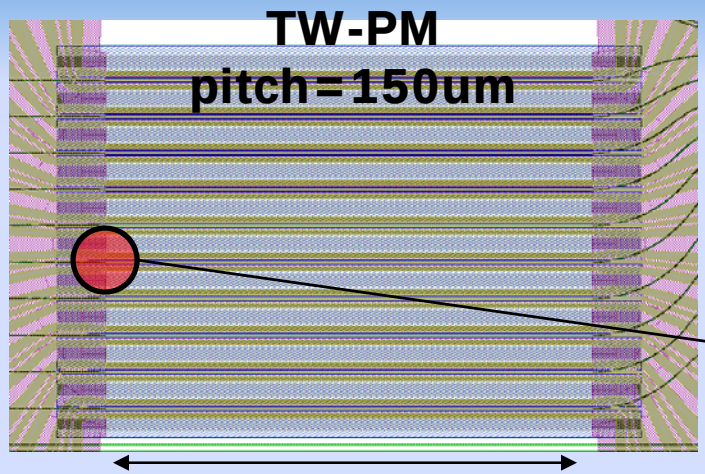
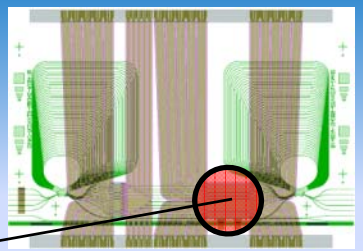
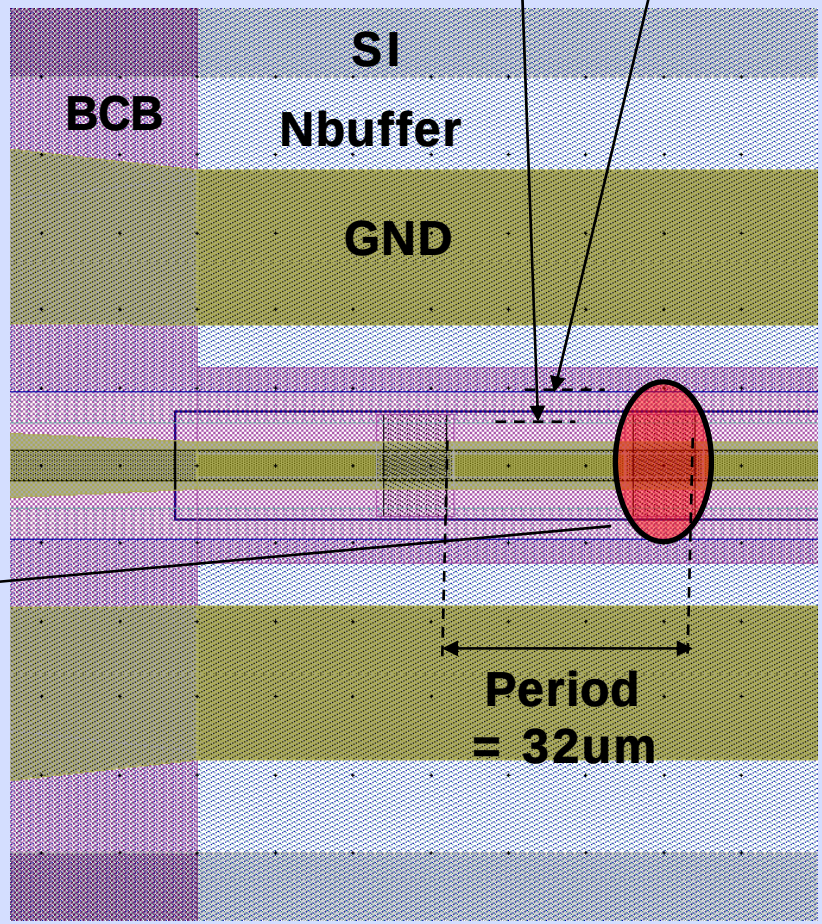
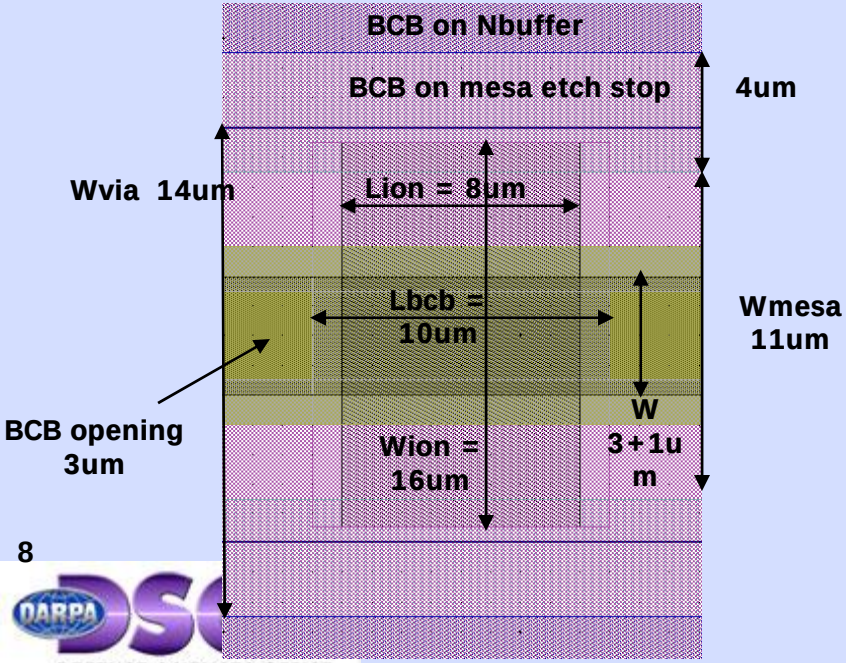
OAWG-TW-PM









sig-gnd-gap: 6-20-15um

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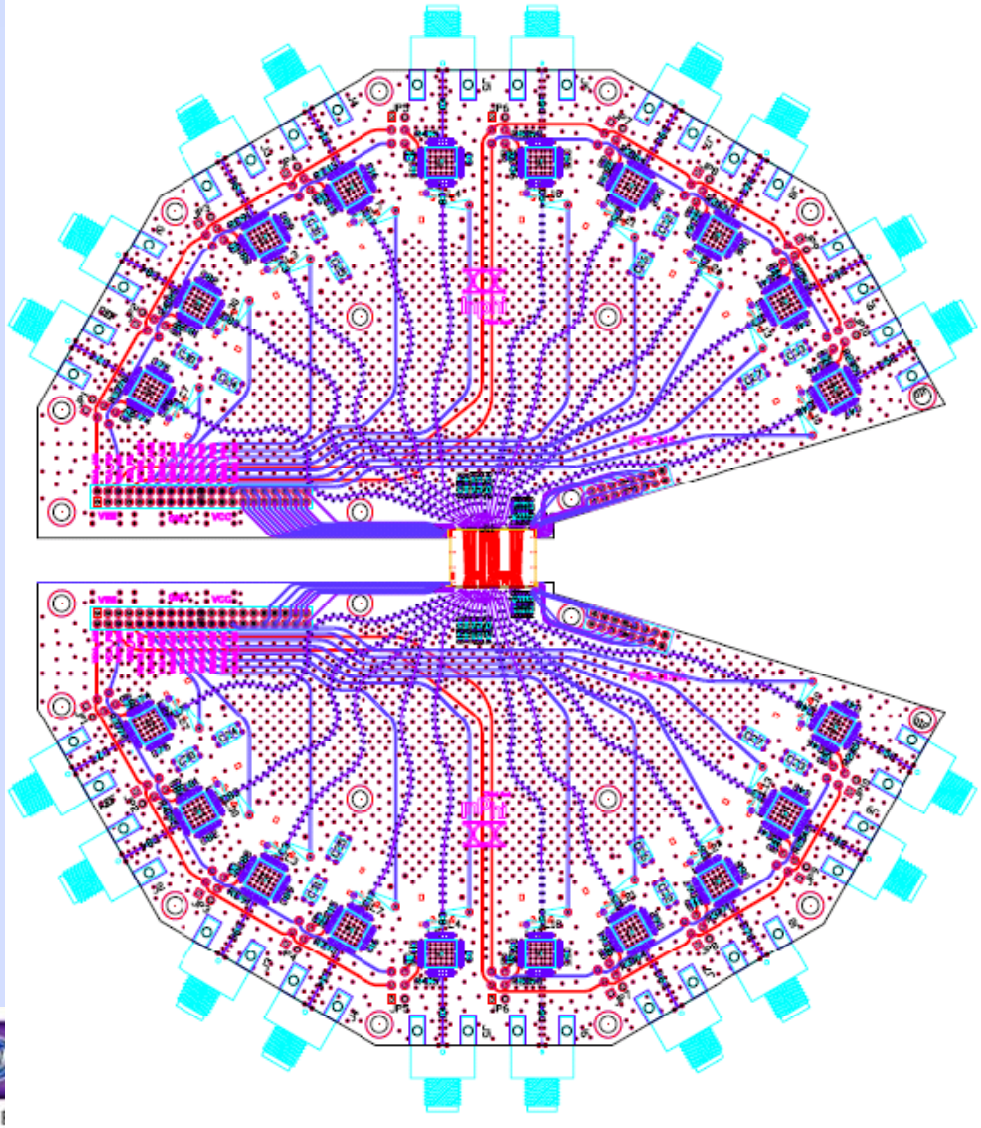
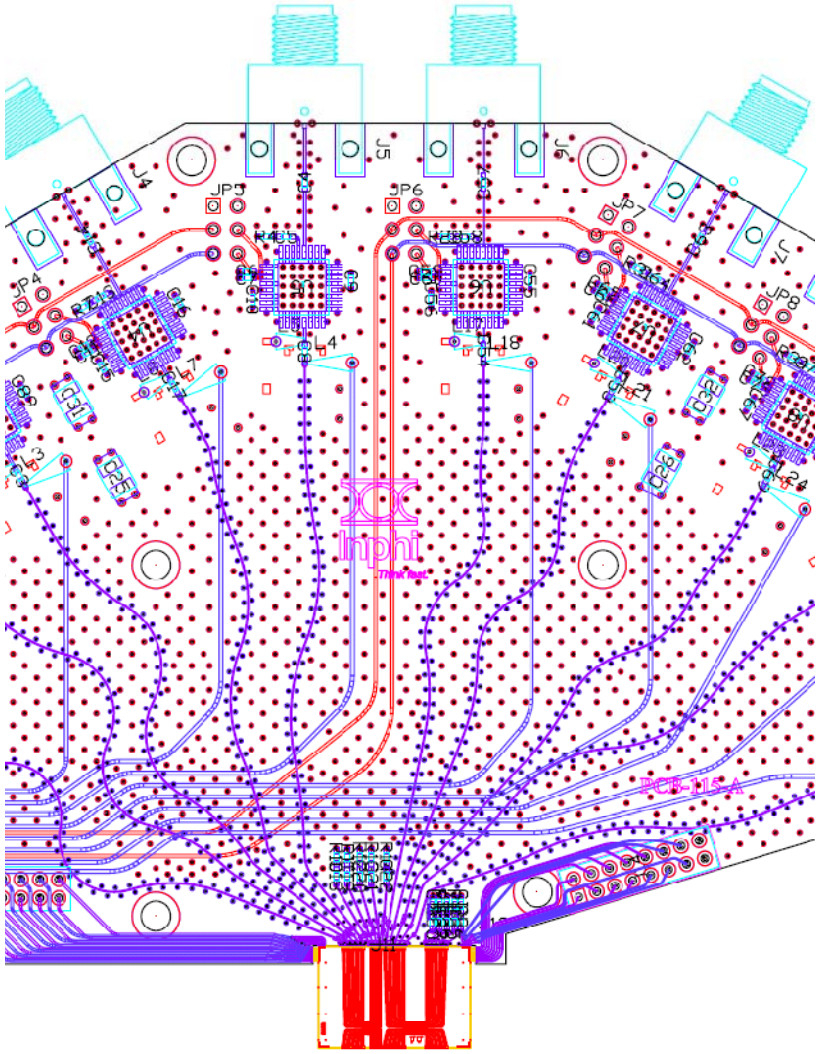
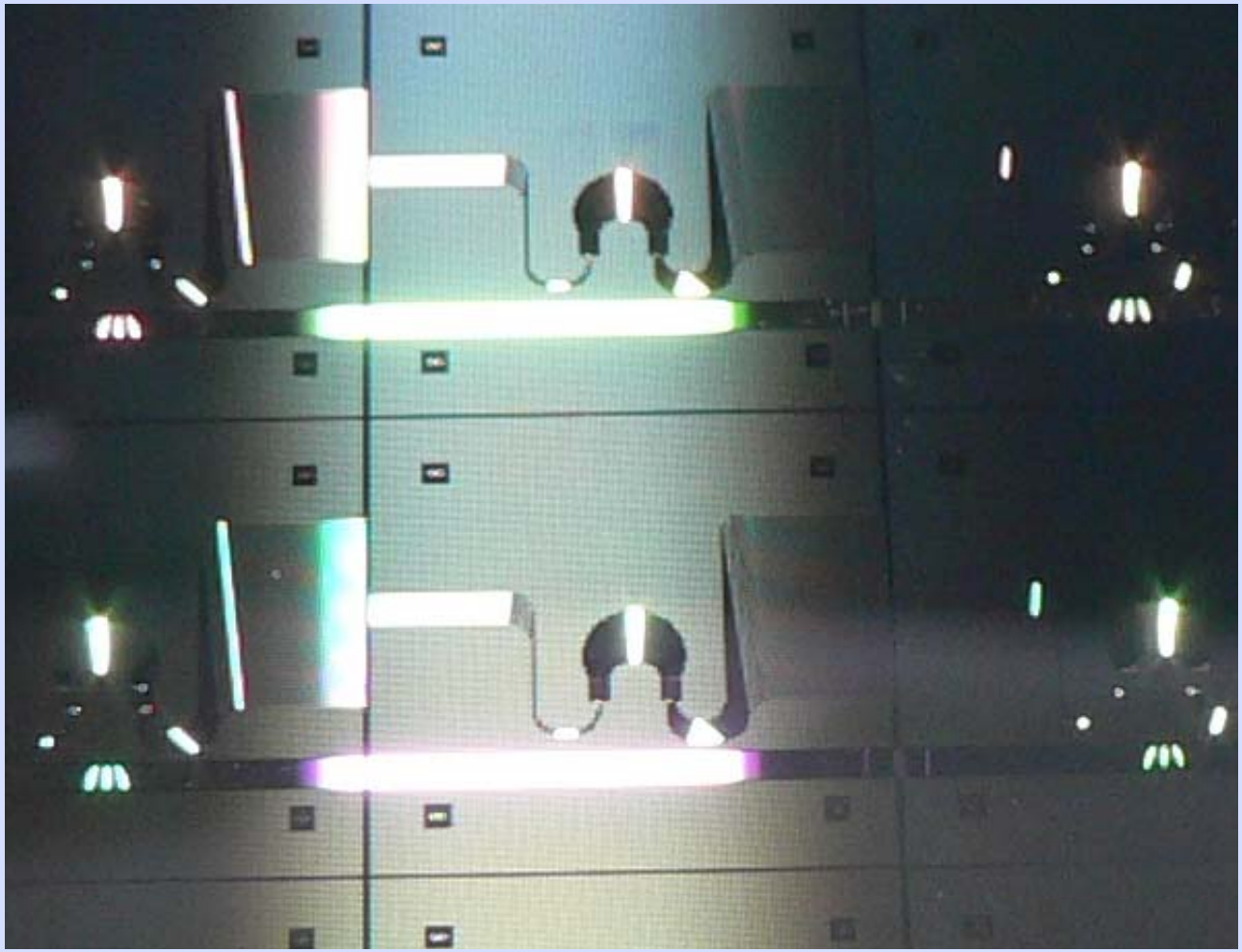
10 Channel AM-PM modulation board





40ch-100GHz Si-AWG die



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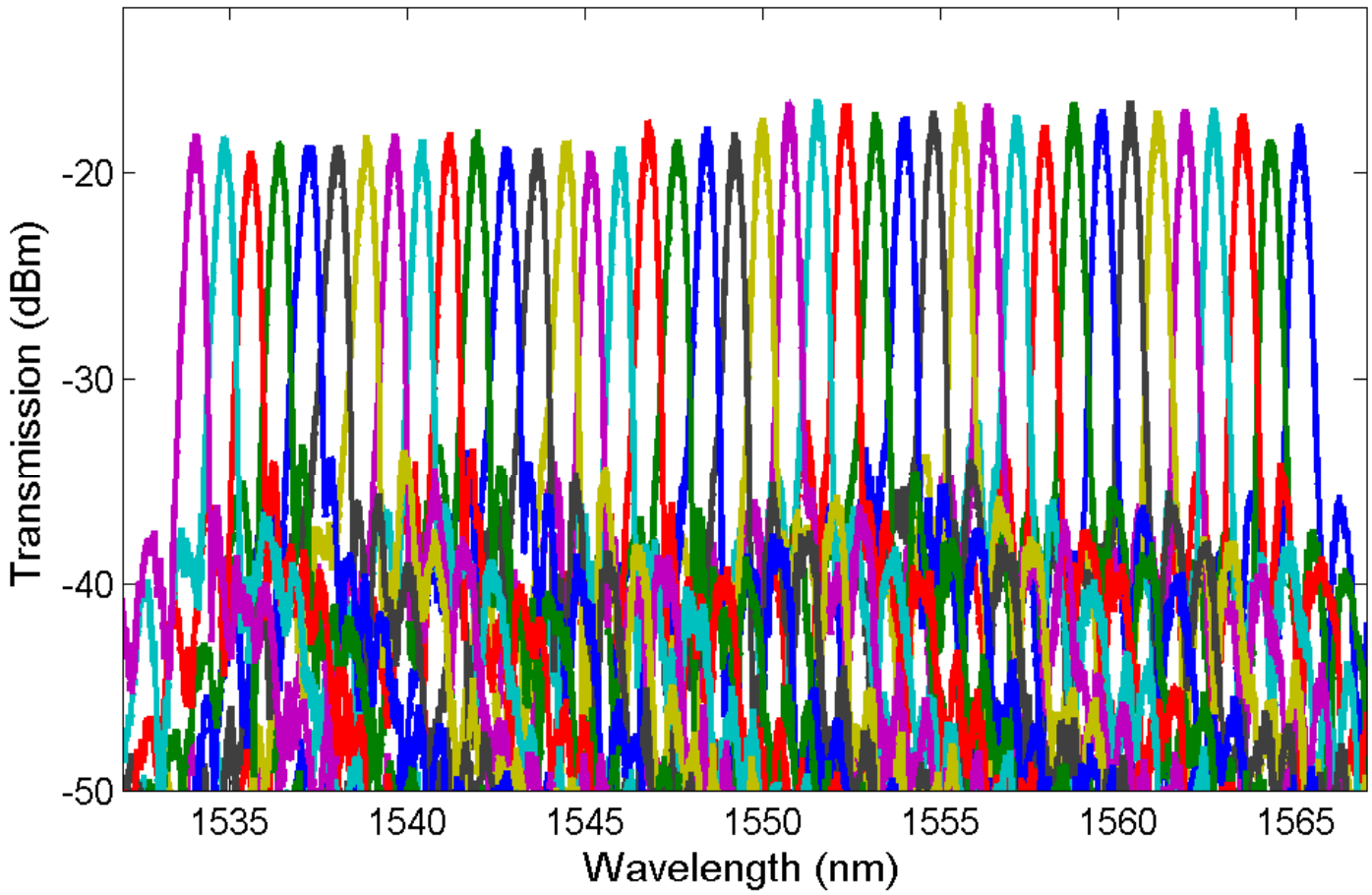
Measured transmission spectrum



40 ch x 100 GHz

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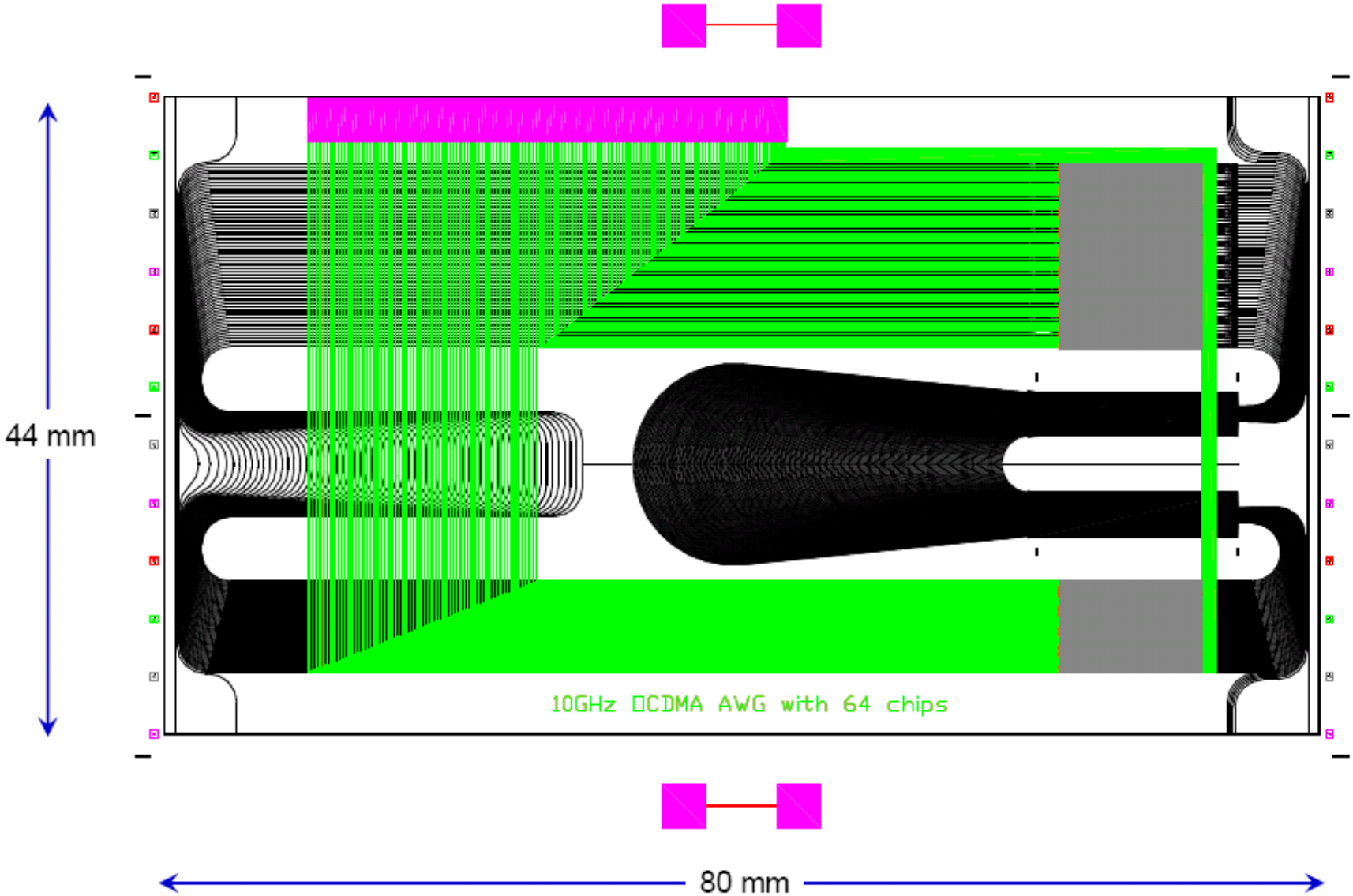
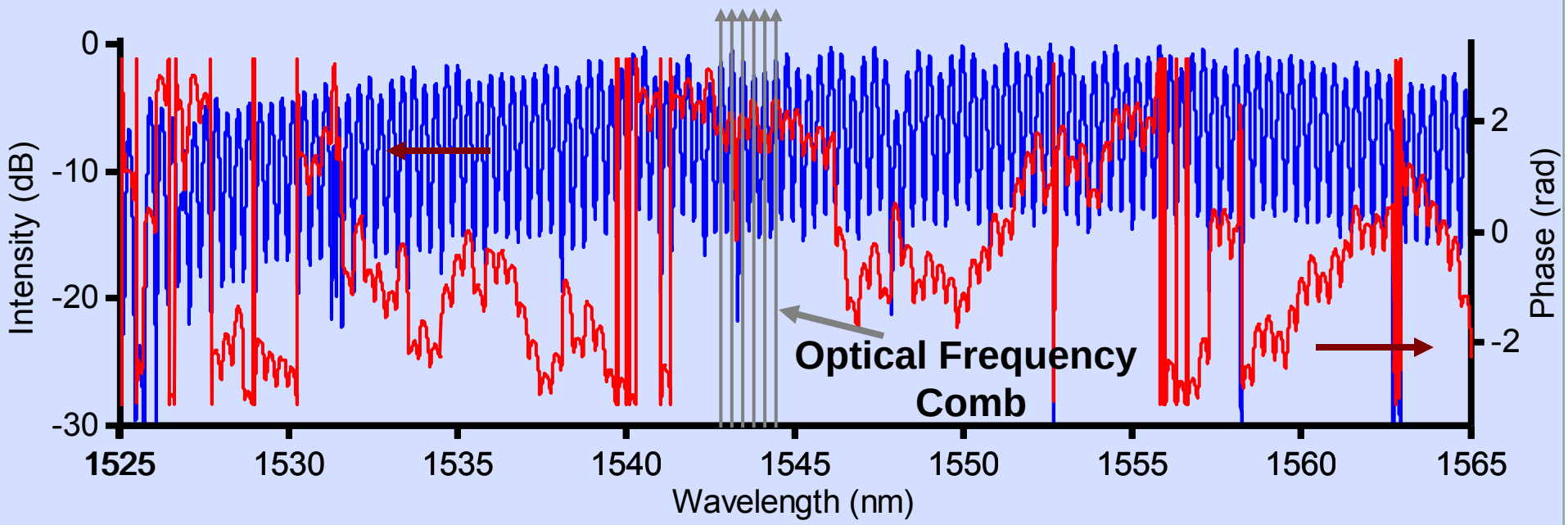
10 GHz X 64 Channel Silica Folded OAWG



40 GHz x 128 channel (~5 THz)
OAWG Waveform Shaper Transmission



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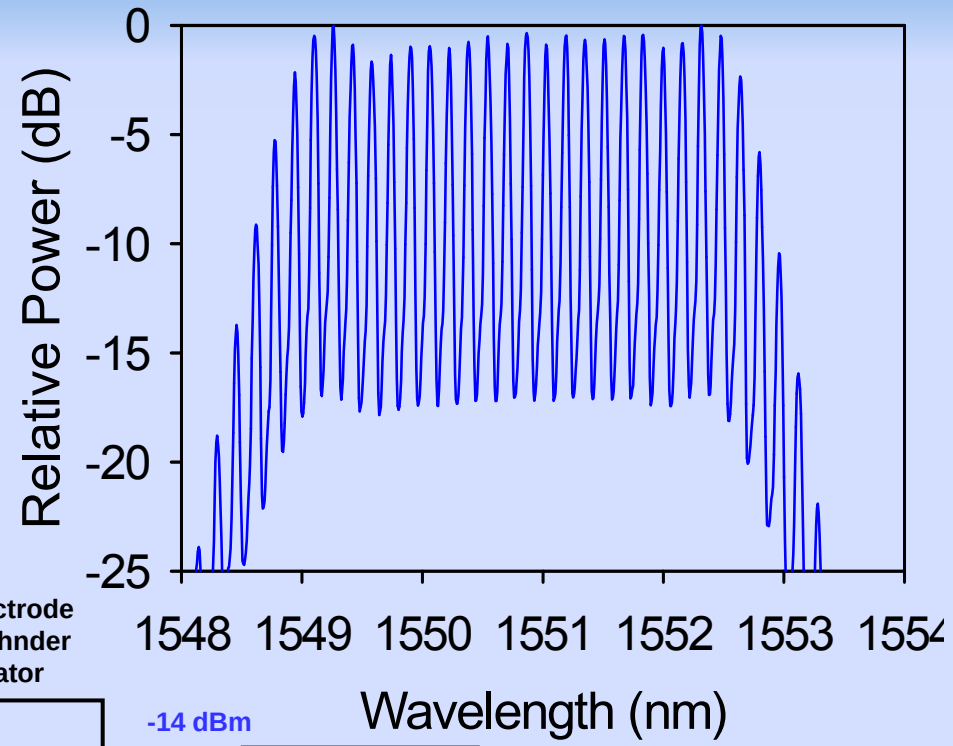
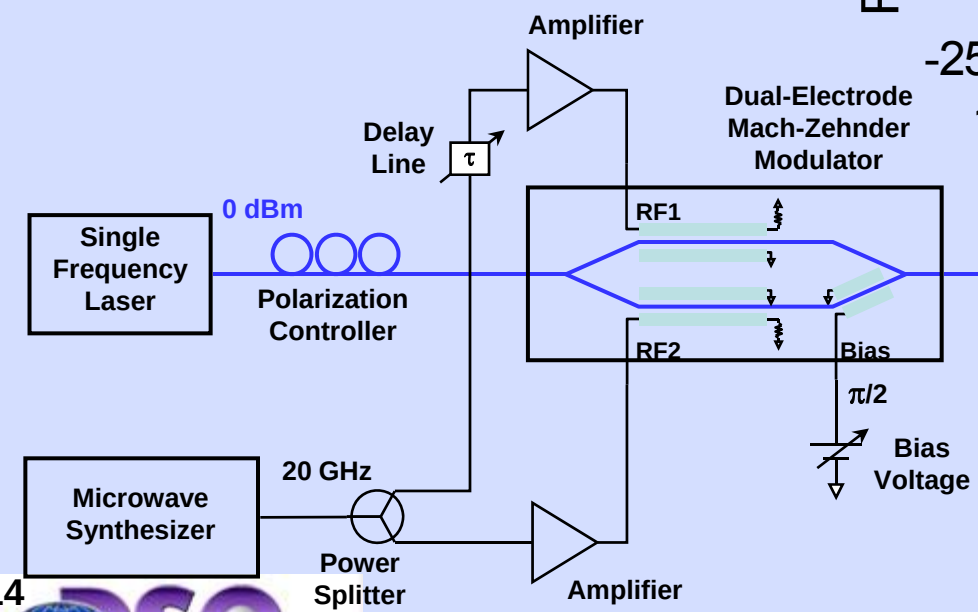
AM/PM Optical Comb Generation

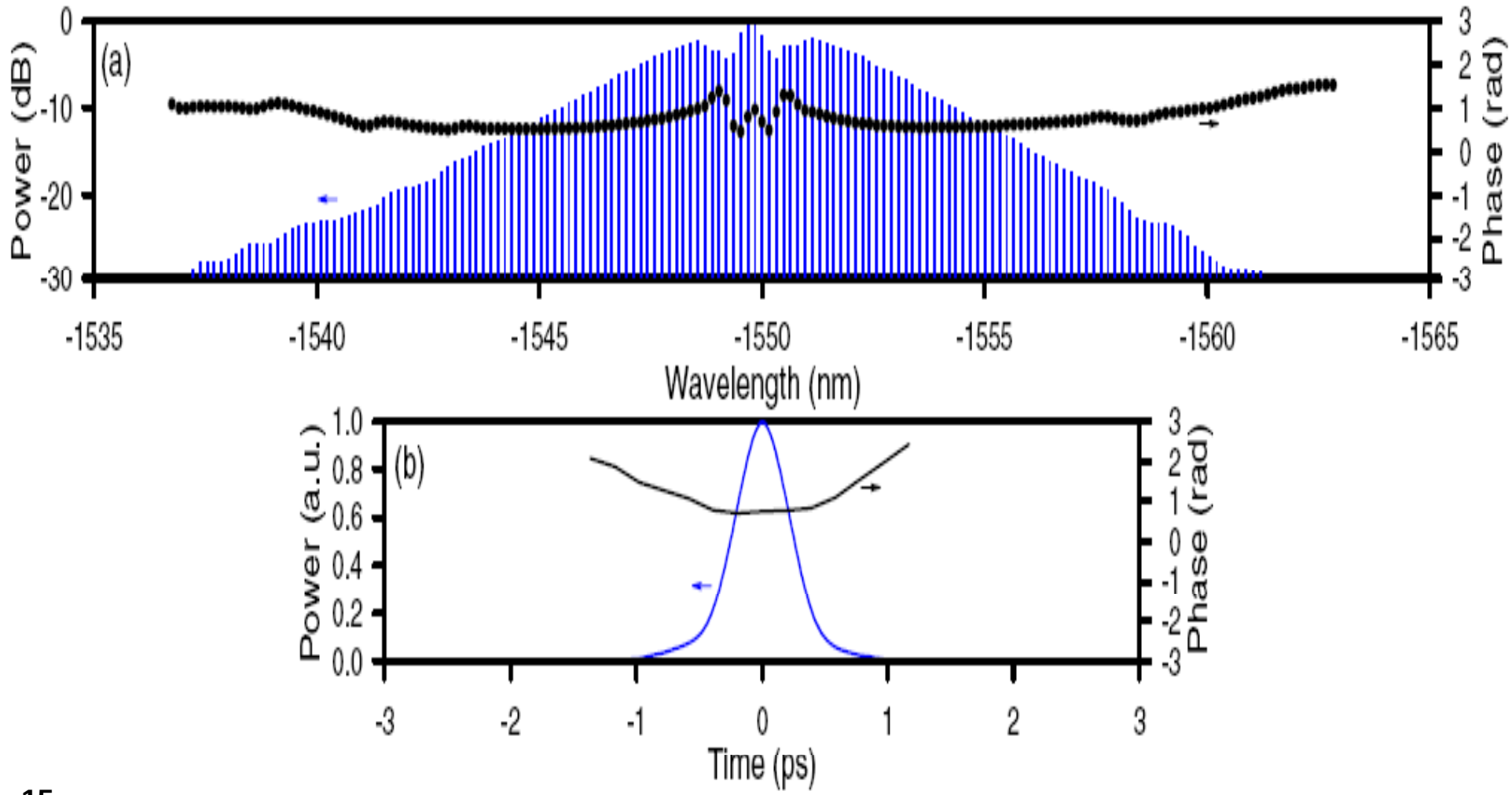
Dual-Electrode MZM with controlled phase and amplitude modulation for a maximally flat comb line generation.





Ref. T. Sakamoto, et al, Optics Letters, Vol. 32, No.11, pp. 1515-1517

175 –line Transform-Limited Optical Frequency Comb



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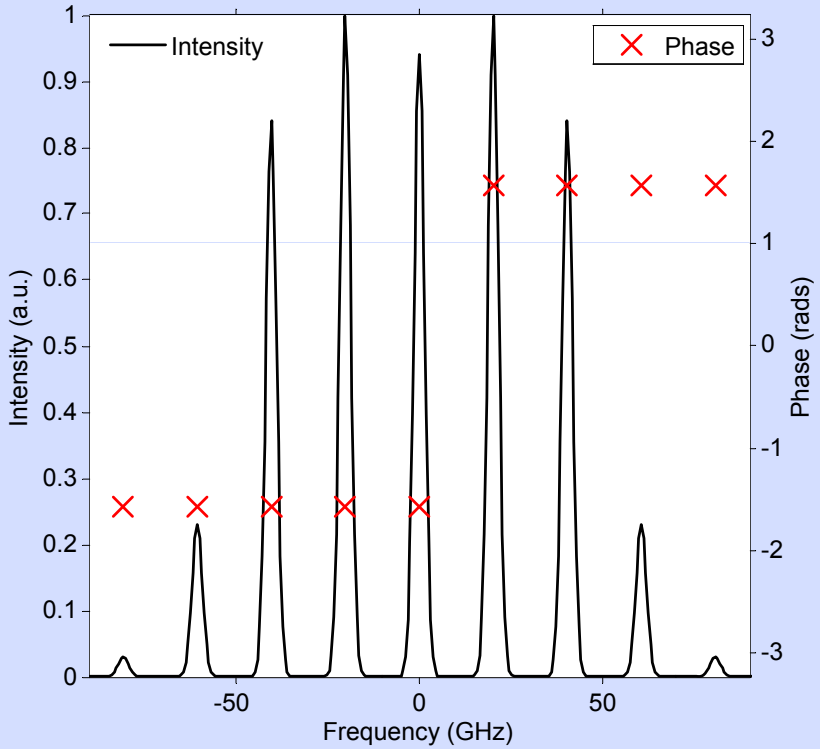
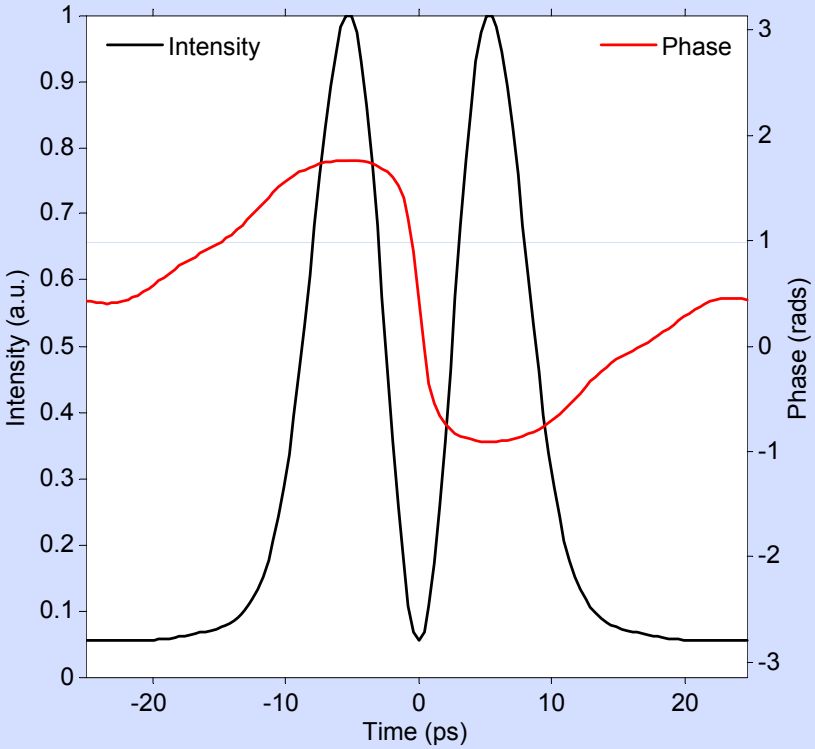
Target Pulse
(0-pi Pulse A)





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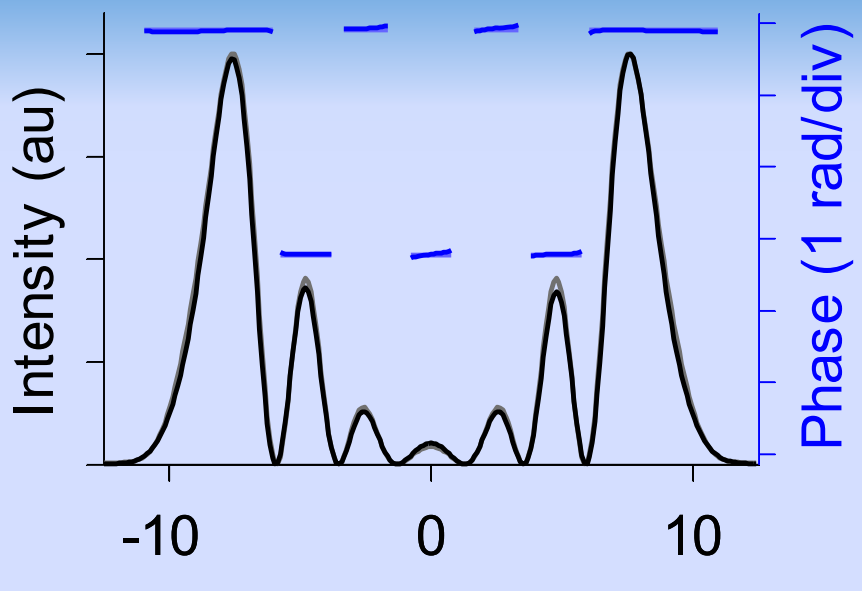
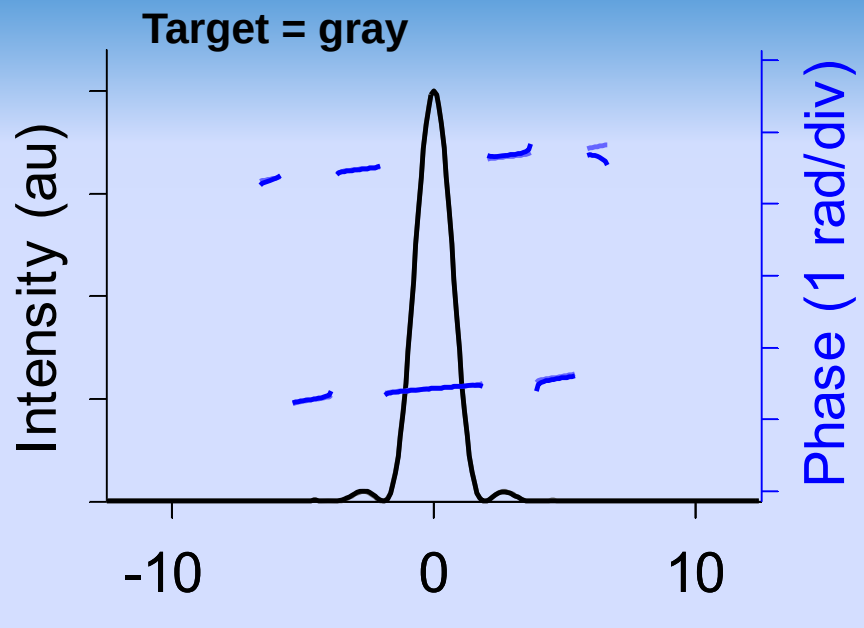
Comparison of Final Shapings





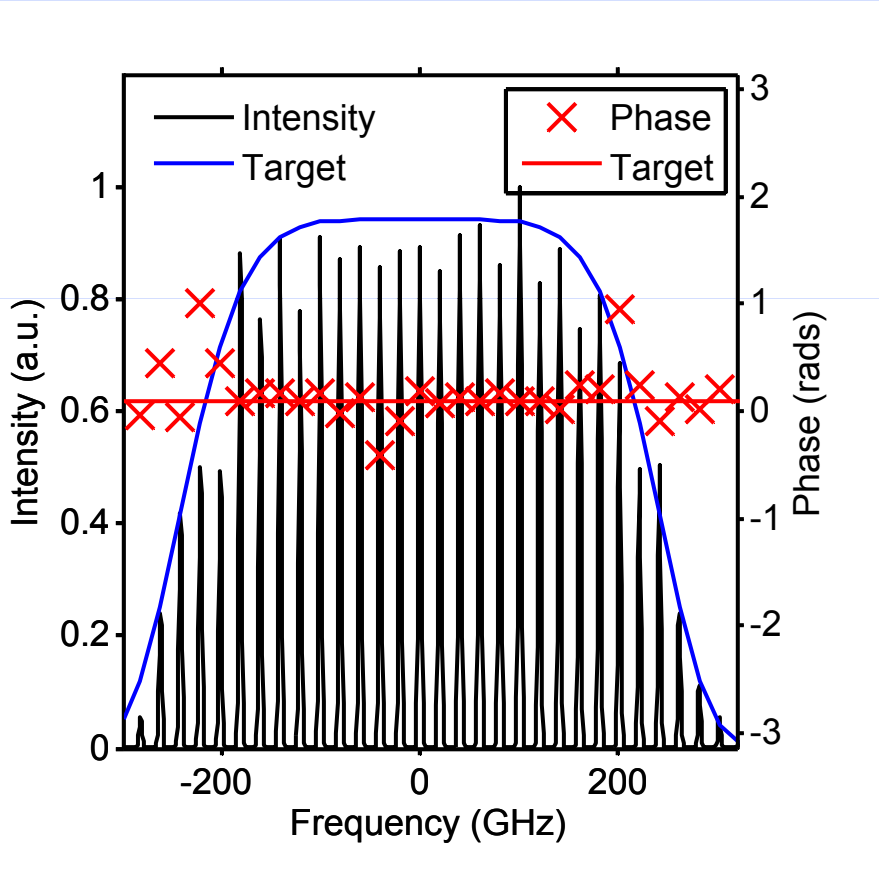
It.	G' %	ϕ (rad)	I.E. %
1	67.00	16.80	12.0
2	14.00	1.60	14.2
3	11.54	0.26	10.8
4	3.59	0.89	6.3
5	3.60	0.93	2.4
6	3.53	0.79	2.4
7	3.52	0.29	2.4
8	3.52	0.18	2.4

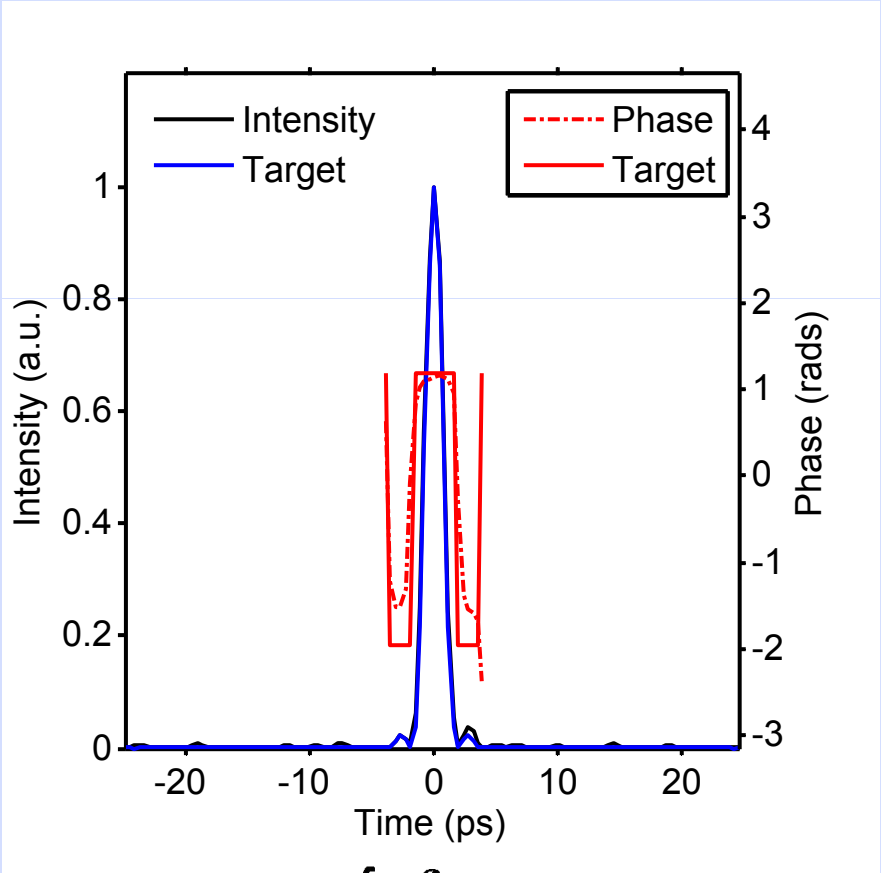
It.	G' %	ϕ (rad)	I.E. %
1	45.01	8.48	7.4
2	10.04	3.83	5.3
3	7.90	1.21	7.9
4	5.72	0.30	5.0
5	4.71	0.21	5.5
6	0.38	0.28	1.2
7	0.37	0.10	1.2
8	0.37	0.13	1.2

Similar waveform shaping errors result in a larger G' for spread waveforms

OAWG Shaped Pulse --unchirped

Transform Limited Pulse with Super Gaussian Spectral Amplitude





*** Super Gaussian is of the form:** $\exp\left(-\left(\frac{f}{250}\right)^6\right)$

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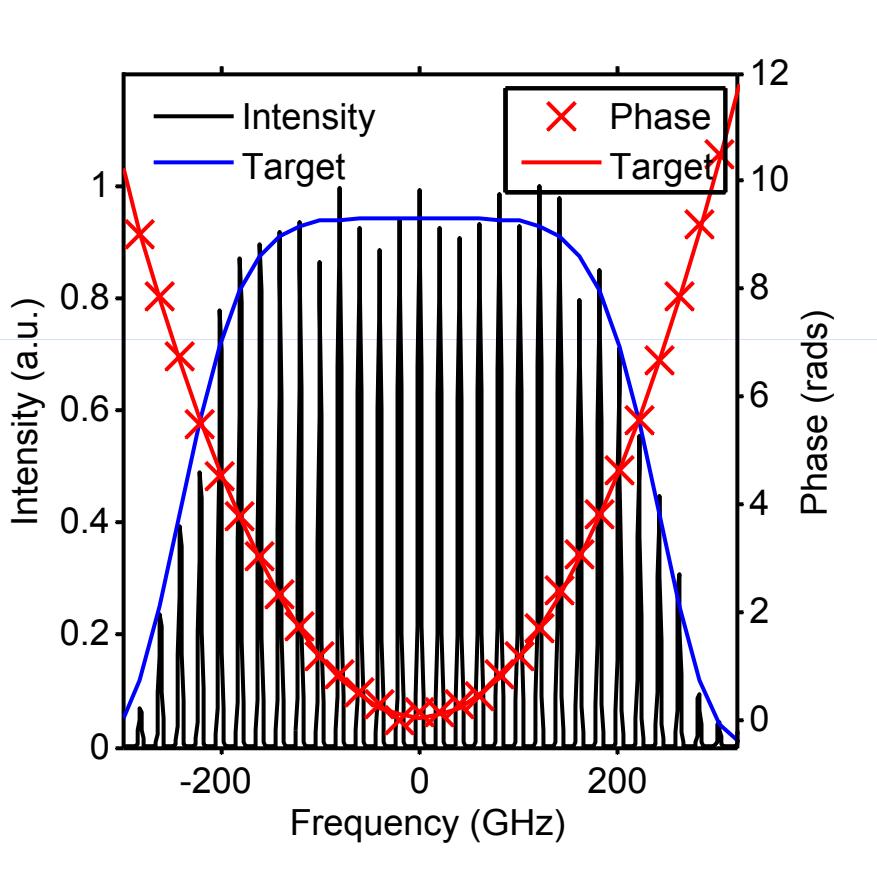
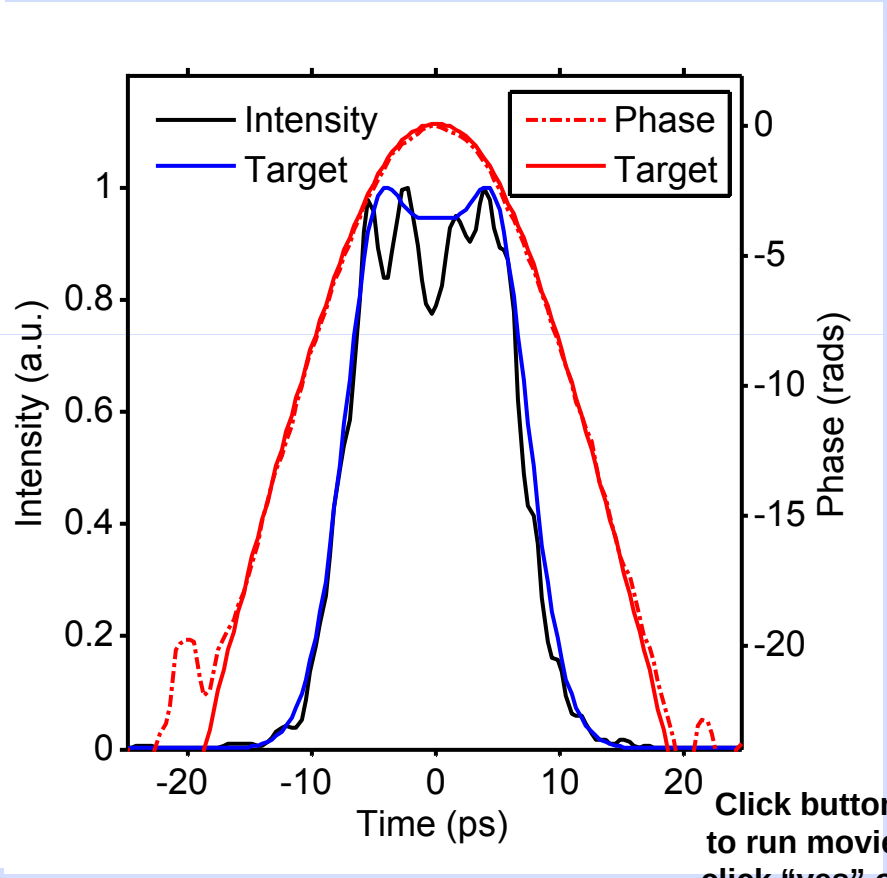
OAWG Shaped Pulse --chirped

Super Gaussian* Spectral Amplitude with Purely Quadratic Spectral Phase
24 Radians over 500 GHz





Click button to run movie, click "yes" on the warning dialog.

*** Super Gaussian is of the form** $\exp\left(-\left(\frac{f}{250}\right)^6\right)$

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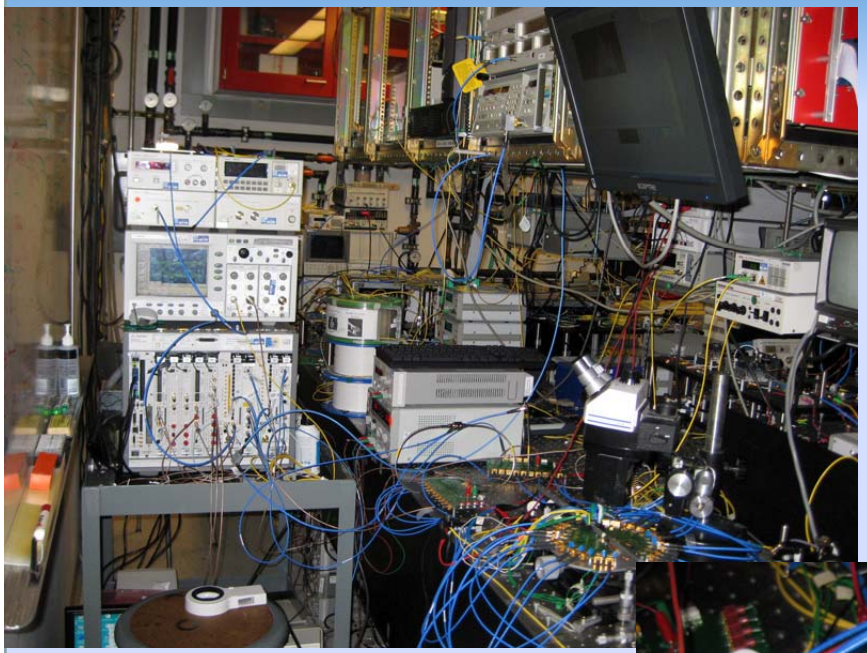
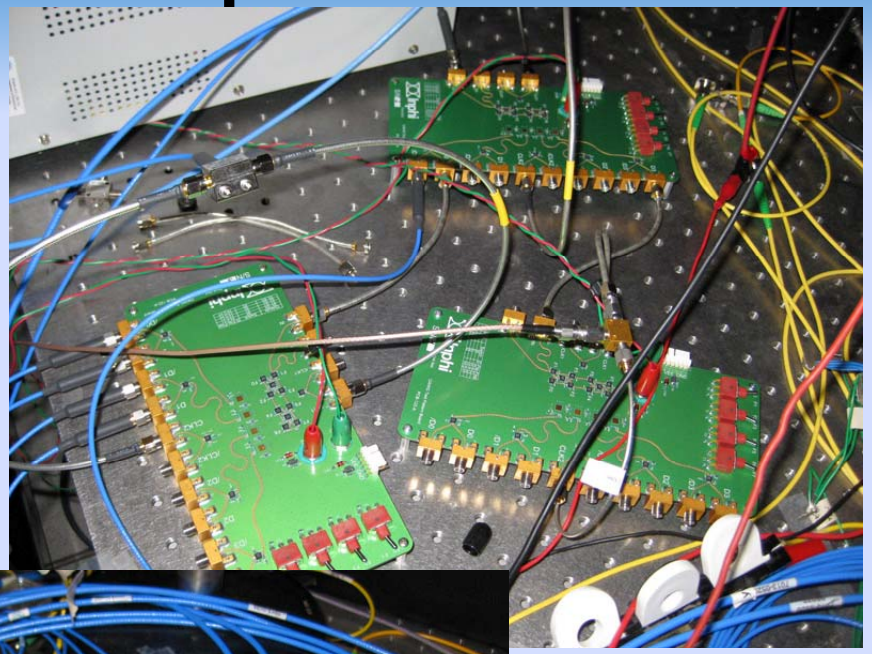
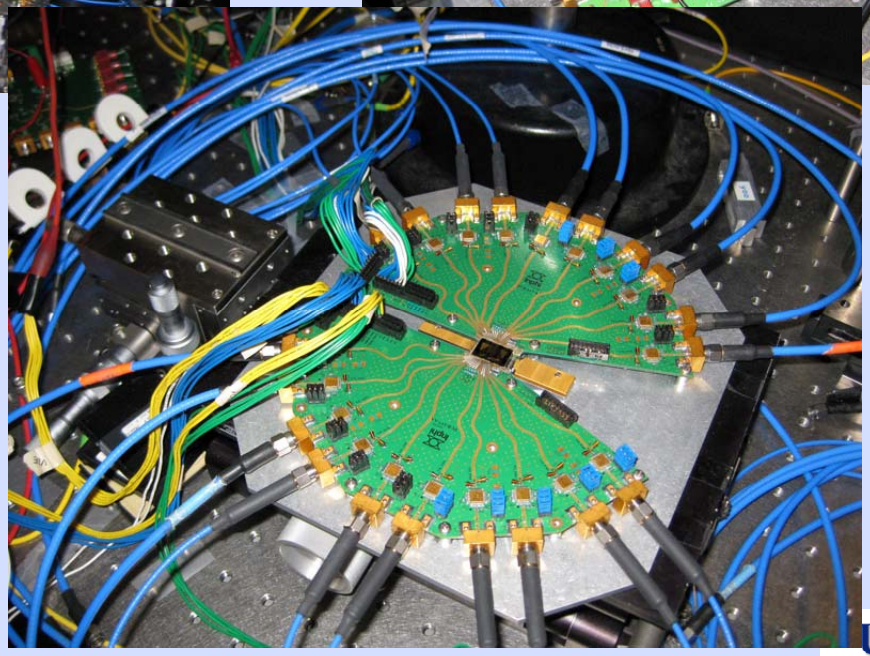
10 chx10 Gb/s OAWG experiment







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Generated Waveforms from InP OAWG encoder

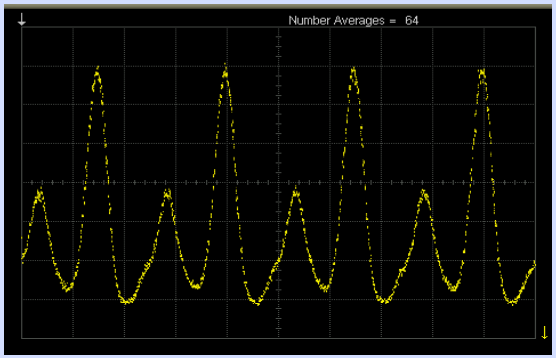

Fig.a 0V

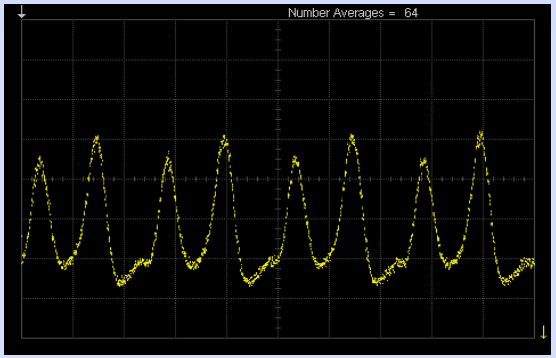

Fig.b 2.5V

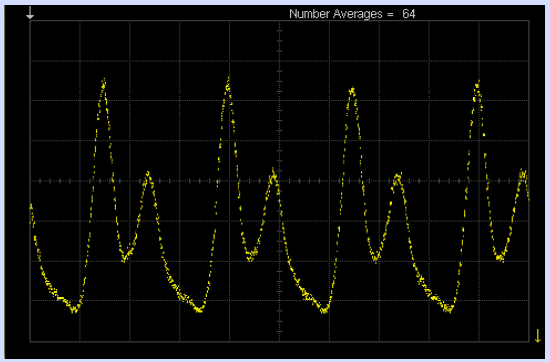

Fig.e 10V

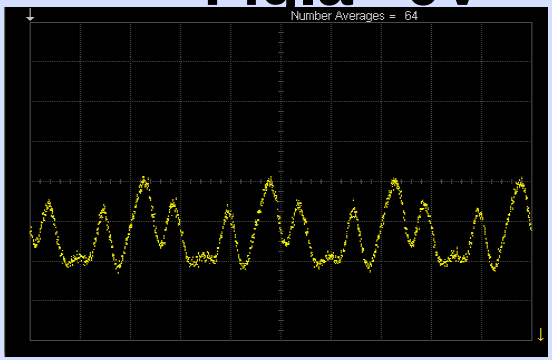

Fig.c 5V

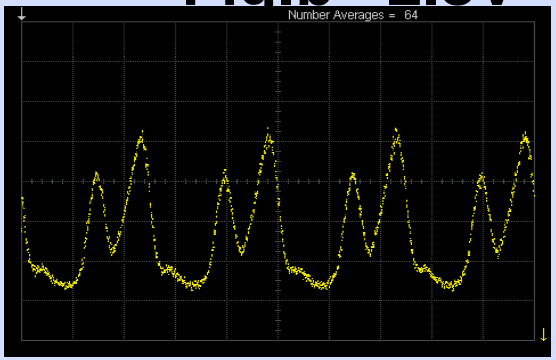

Fig.d 7.5V

Time 20 ps/div

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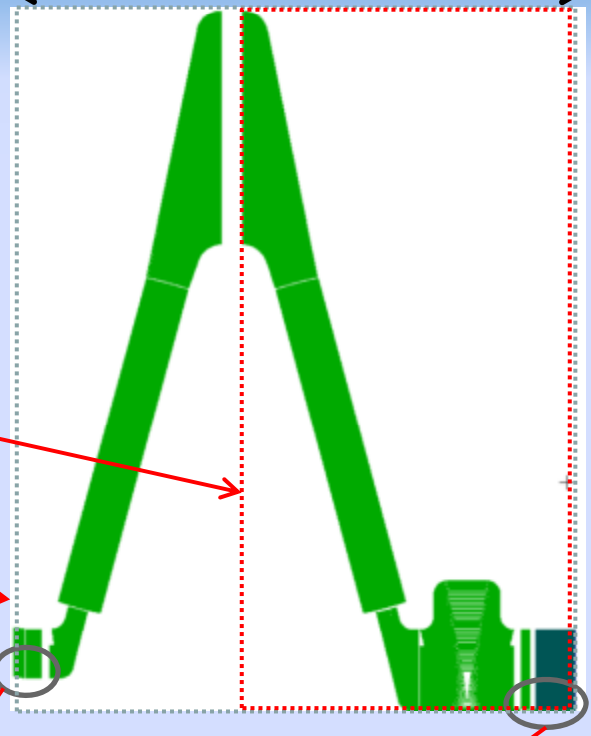
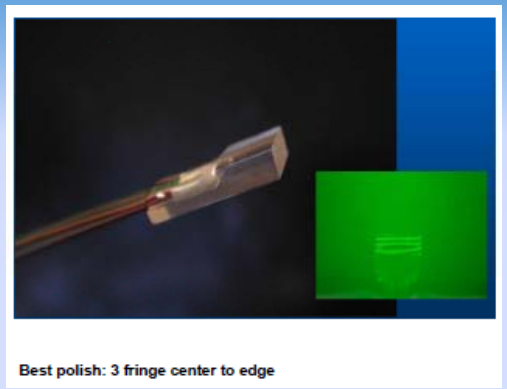
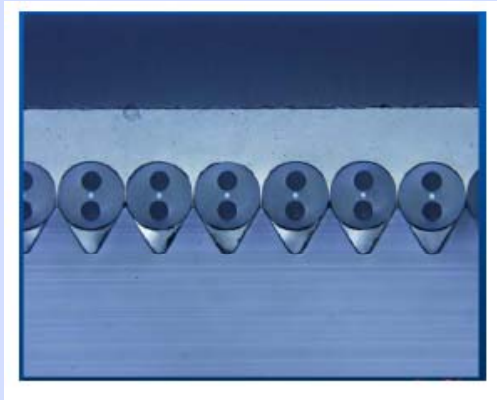
100 Channel Reflective-Type 100 channel OAWG

2.9 cm





3.5 cm



Reflective OAWG device with Reflective AWG

Reflective OAWG device with Full AWG

mode filters

4 MMI input/output (to differentiate input from output)

angled input- and output waveguides

mode filters

2 straight input/output

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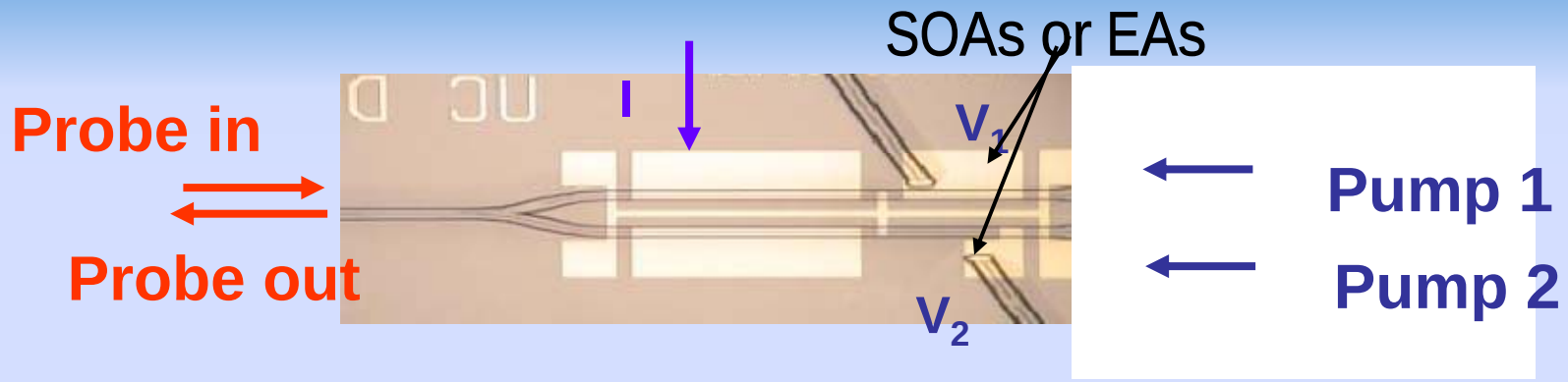
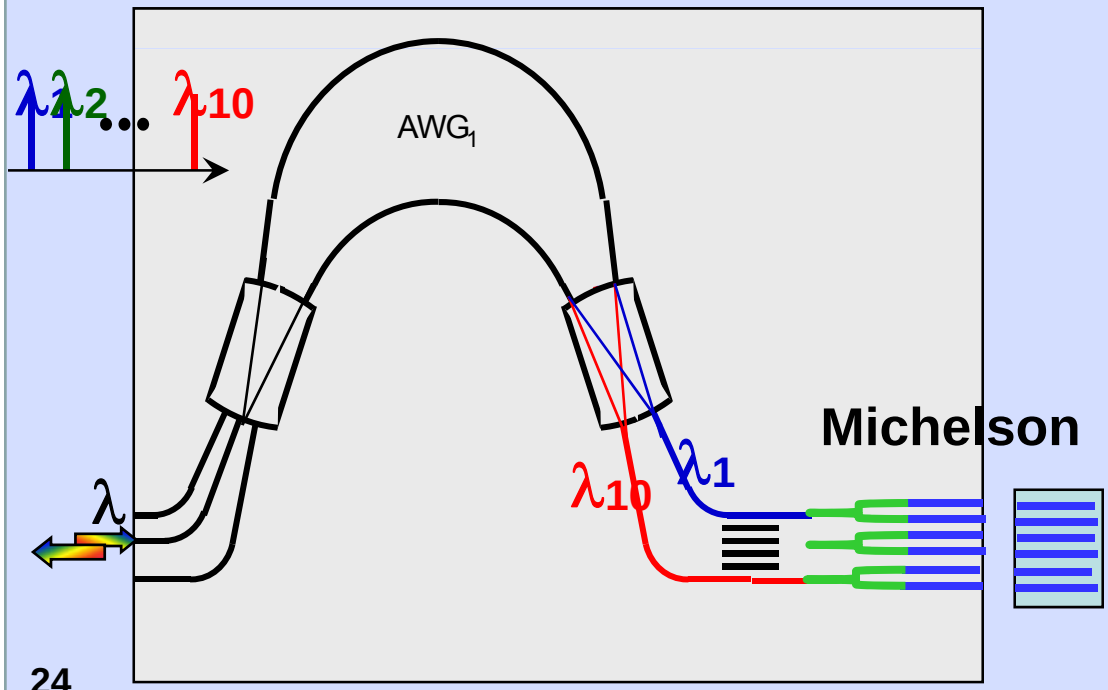
Optically Interconnected OAWG Michelson Interferometer



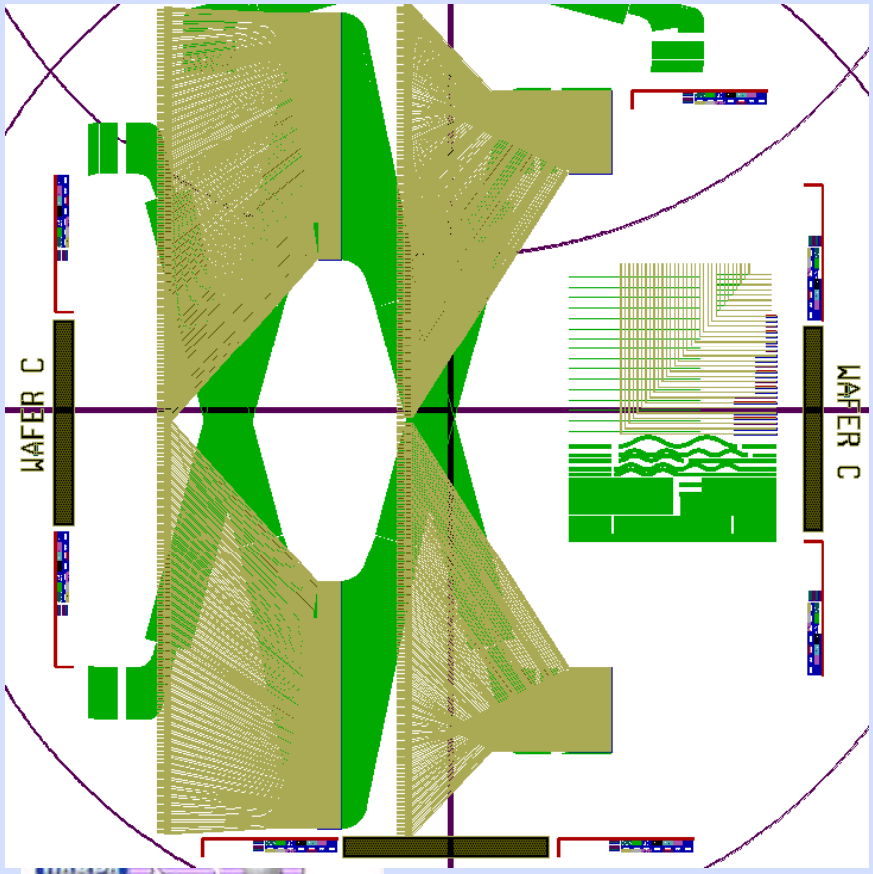


RF wave

- Guaranteed DEMUX-MUX alignment
- Low loss optical pump coupling
- Independent amplitude and phase control
- Short optical active device (< 1 mm) to achieve > 10 GHz bandwidth

Fabricated 100ch x 10 GHz OAWG encoder device

Mask Layout



Photograph of Fabricated Device

(after metalization)

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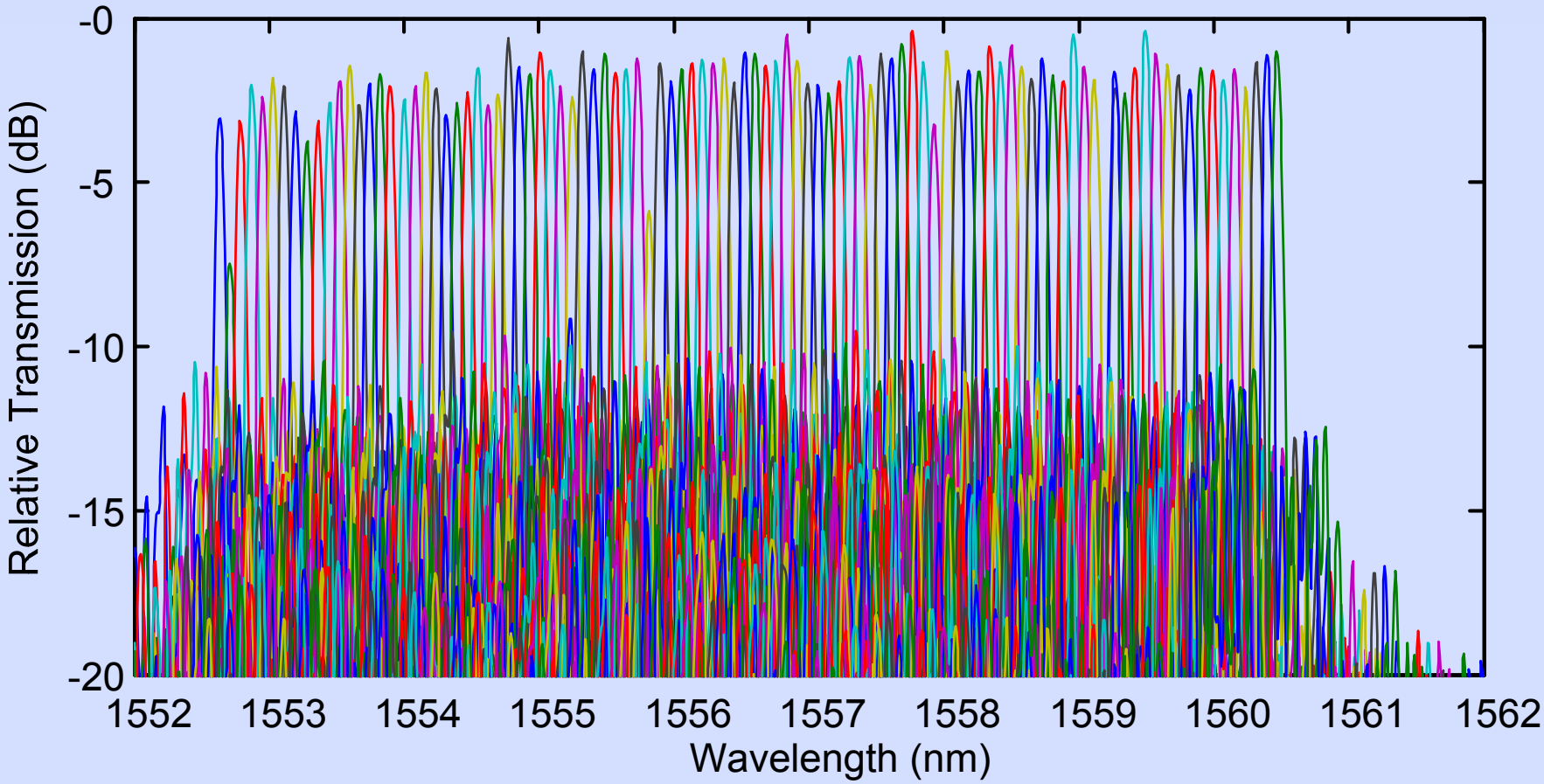
Measured AWG Transmission After Phase-Error Correction (100 channel measurement)



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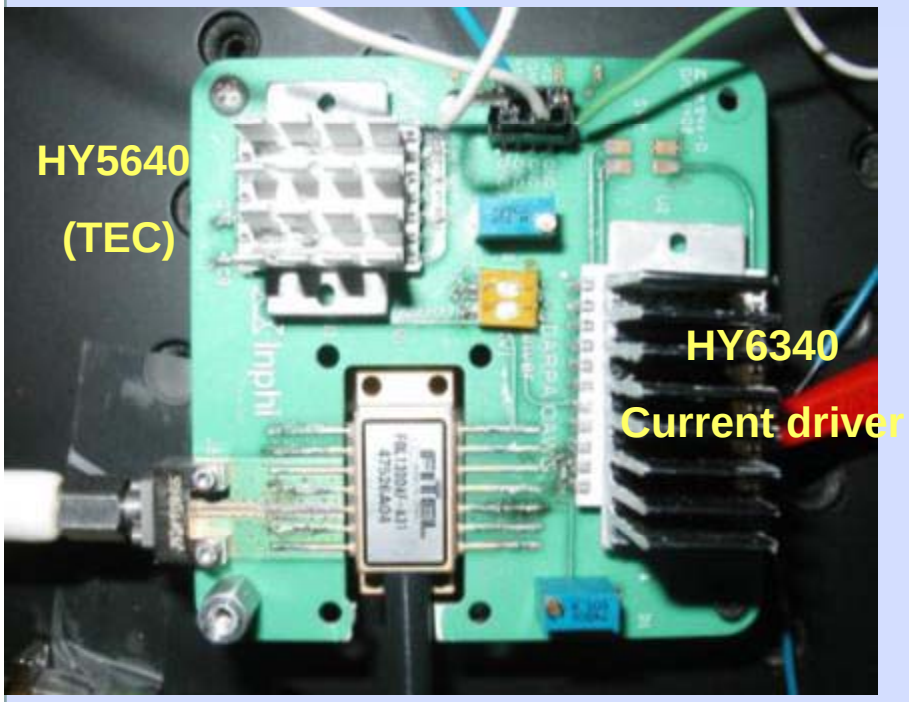
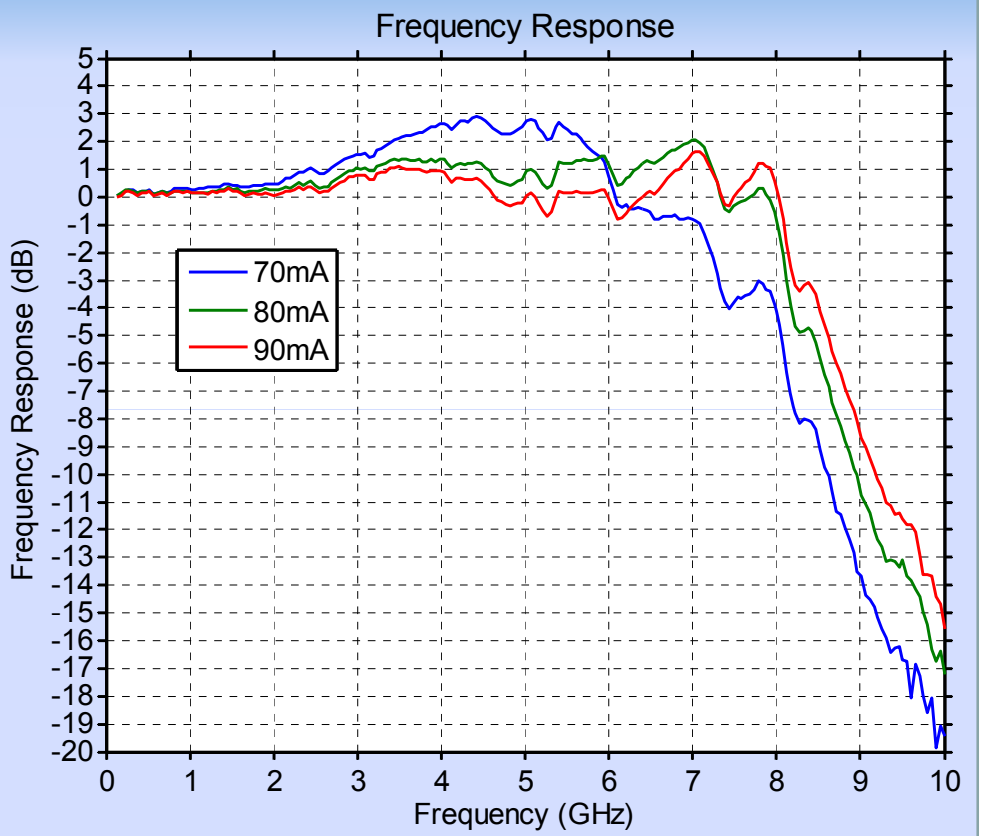
1310 nm Interconnection Lasers





100 ch x 10 GHz OAWG with Optical-interconnect

- 40~60 lasers (4~6 boards) drivers with 10 GHz response
- Third vendor analog drivers
- PRBS Port Duplicator x 3

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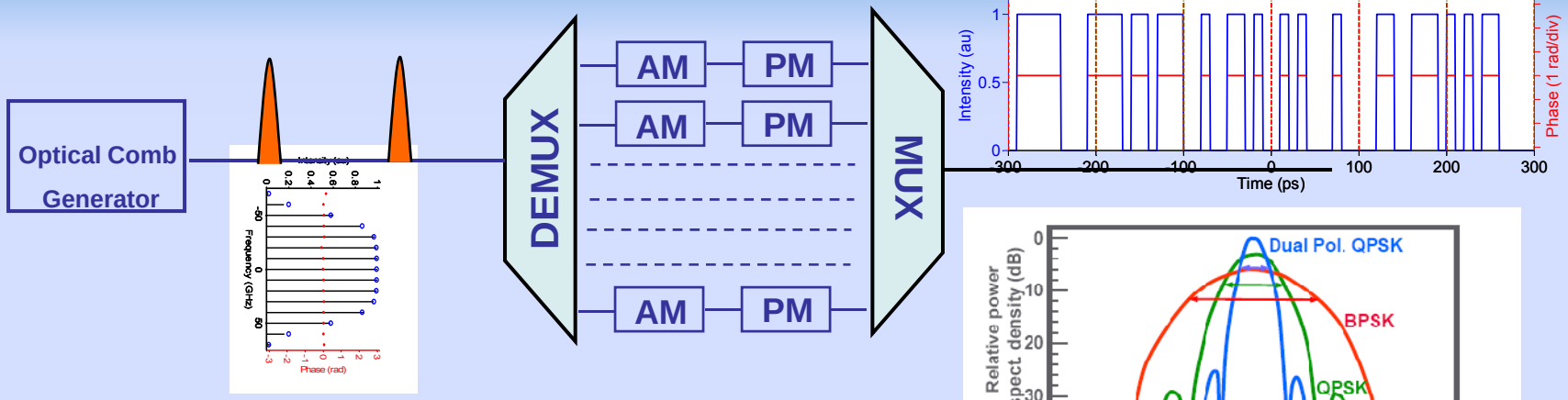
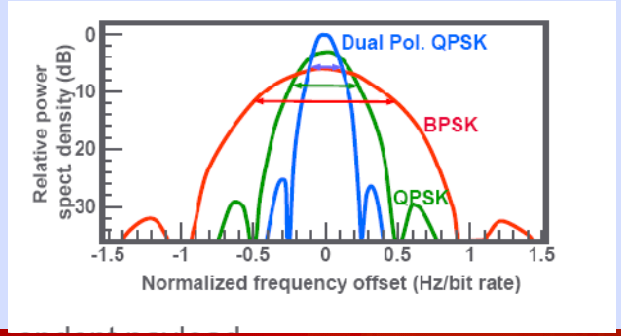
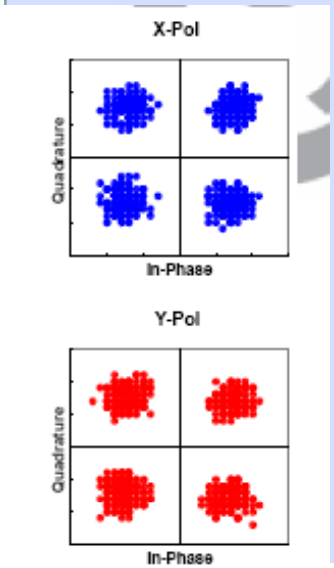
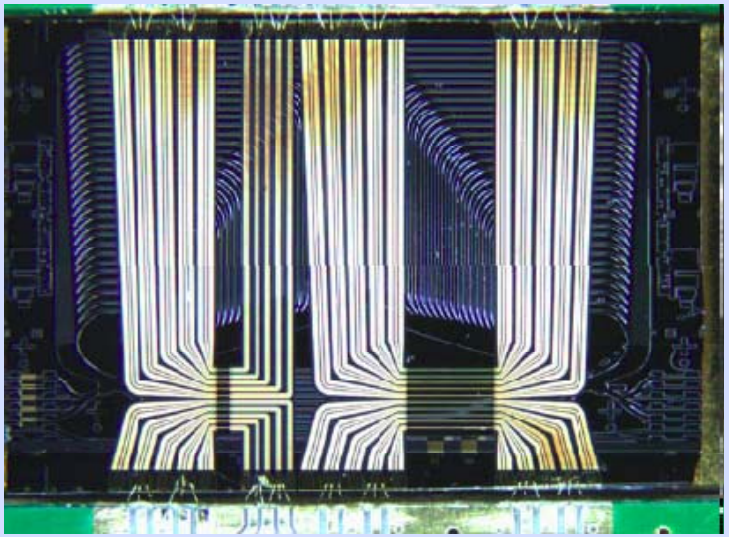
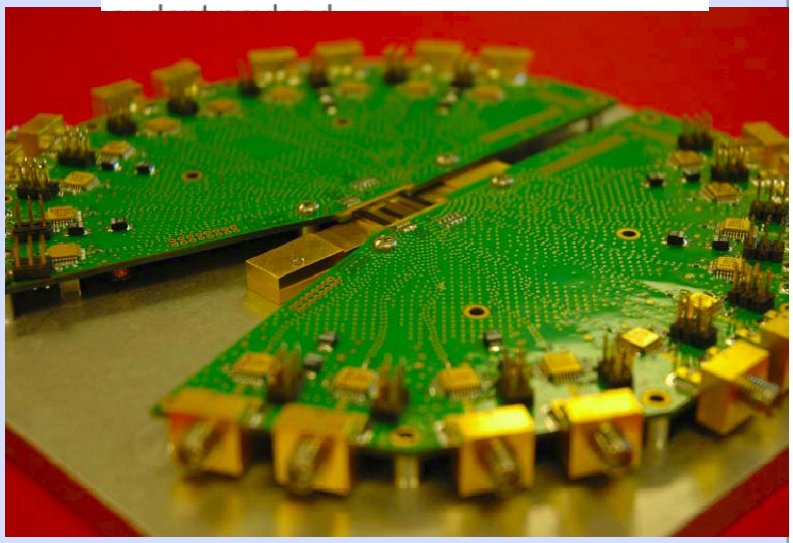
OAWG based 100 G~1Tb/s Transmission with ~10 G electronics





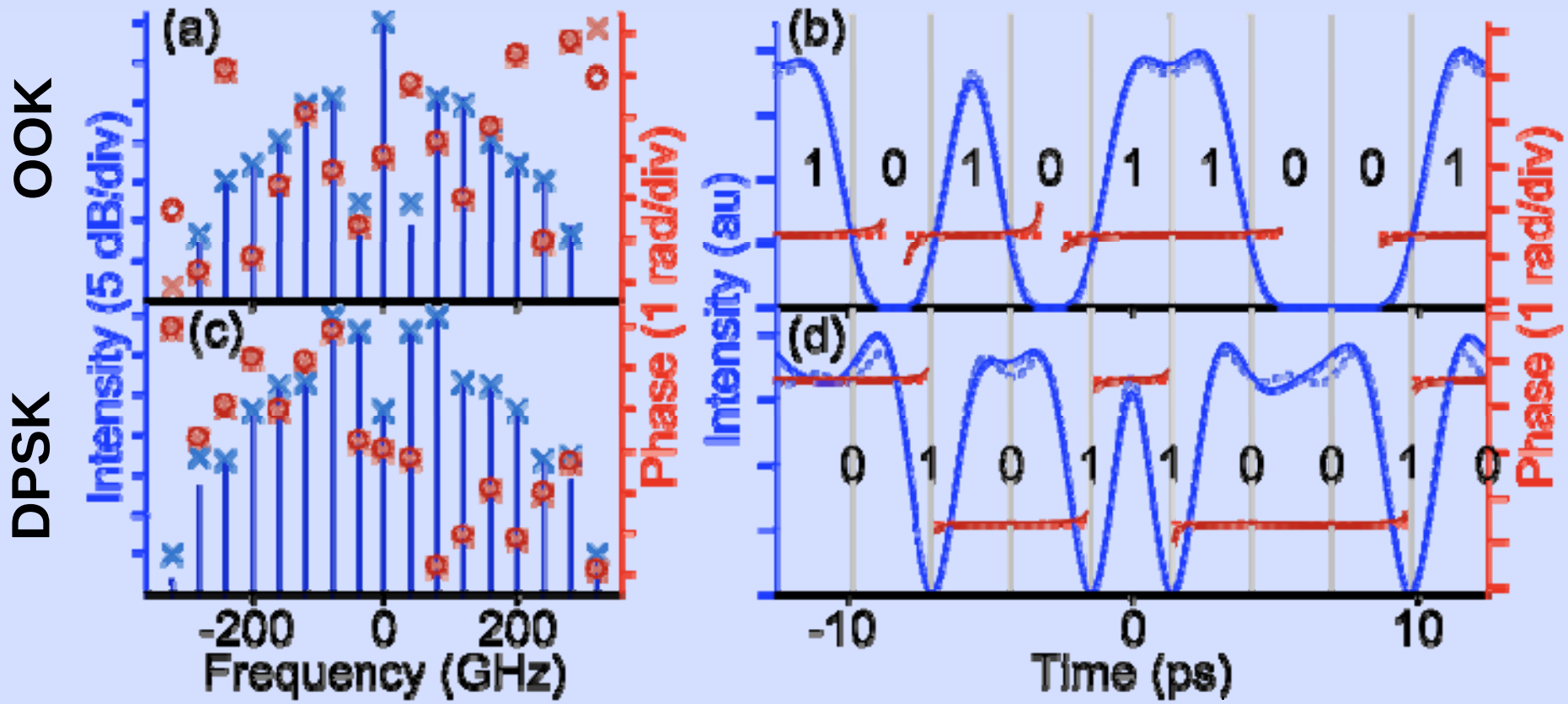






- At a glance, this is useful for parallel 40G/100G Trx/Rcv with independent ASK, PSK, DPSK, QPSK, DQPSK, etc.

360 Gb/s PRBS Data OOK & DPSK (experiment)



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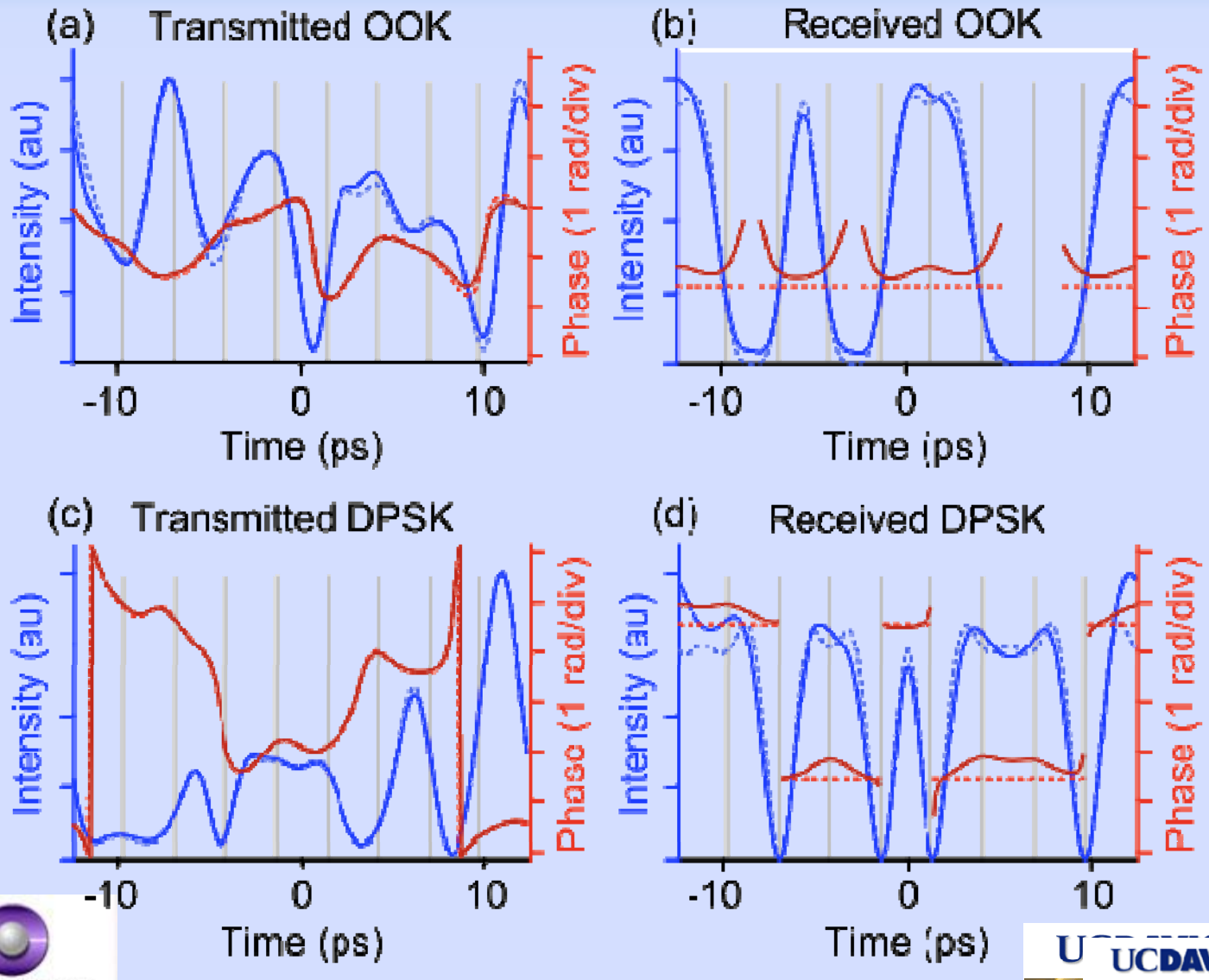
Predistorted 360 Gb/s 10 km Single Mode Fiber Transmission Results

OOK

DPSK



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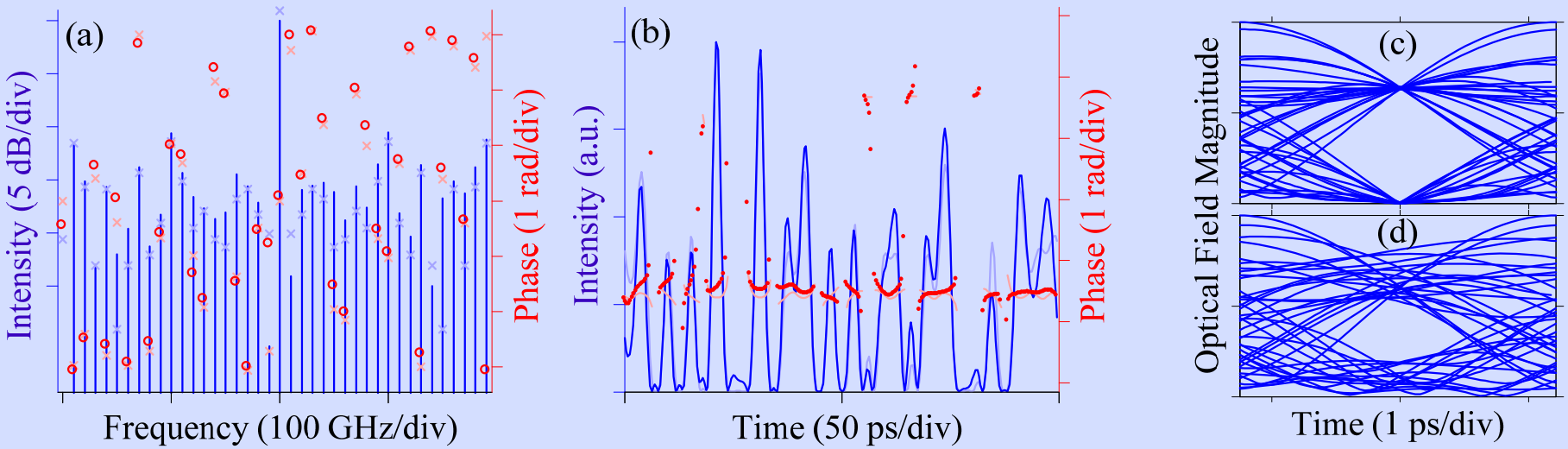
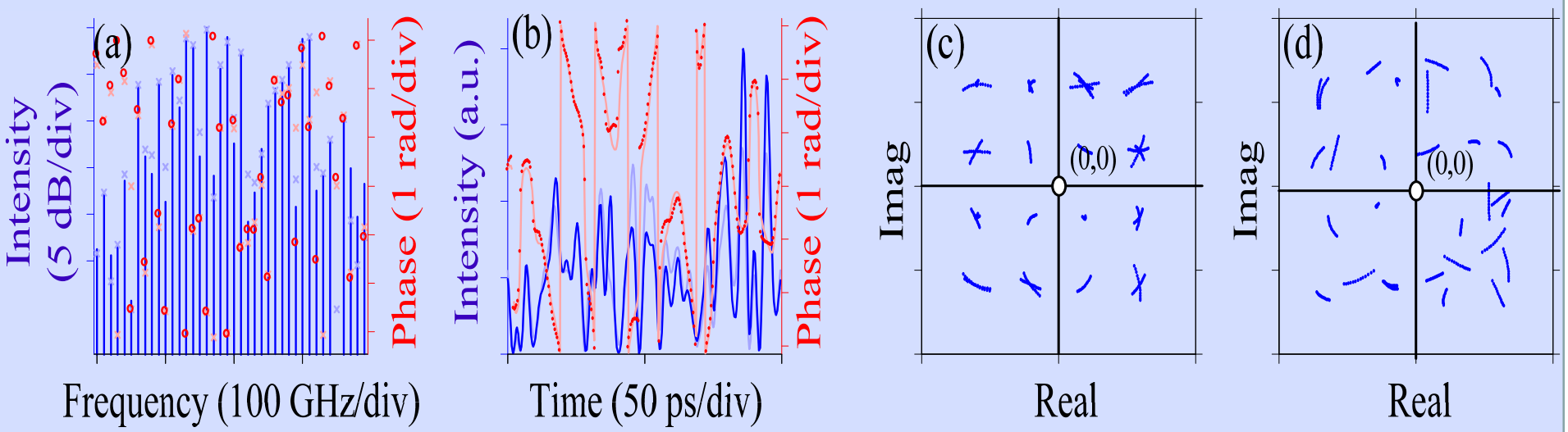
400 Gb/s NRZ-OOK PRBS generation 1 bit/s-Hz



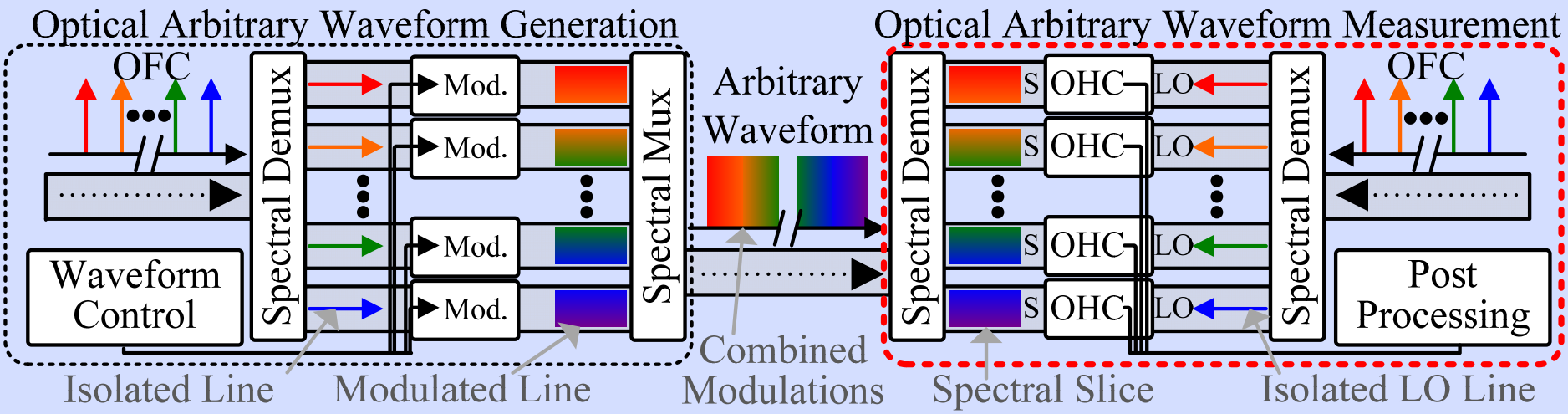
400 Gb/s NRZ-OOK PRBS generation (40-bit-length) (a) Spectral domain (blue) intensity and (red) phase targets indicated by 'x'. (b) Time-domain optical field (blue) intensity and (red) phase. Target packet indicated by lighter shades. (c) Target and (d) measured eye diagrams.

1.2 Tb/s NRZ-16QAM PRBS with 3 bit/s-Hz



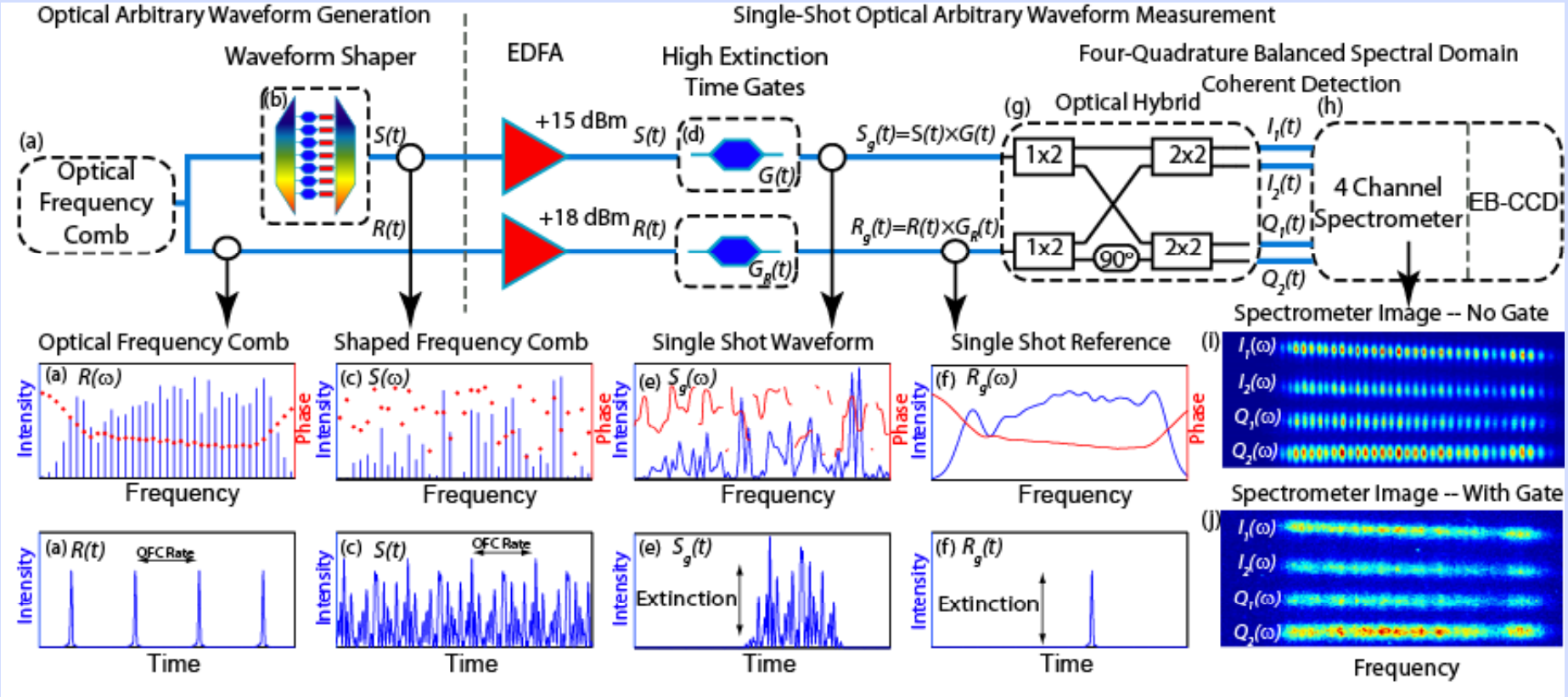
120 bit 1200 Gb/s NRZ-QAM packet (a) spectral intensity (blue) and phase (red), and (b) optical field (blue) intensity, (red) phase. Target indicated by lighter shades and 'x'. (c) Target and (d) measured constellation diagrams.

Optical Arbitrary Waveform Measurements



- **Spectral slices of the signal (S) are coherently detected using a 90° optical hybrid circuit (OHC) and a single mode from the LO OFC**
- **Fast photodiodes (bandwidth>spectral slice width) measure the four OHC outputs**
- **Post processing reconstructs signal from measured outputs**

Schematic Configuration of the Single-Shot Optical Arbitrary Waveform Measurement



N. K. Fontaine, R. P. Scott, C. Yang, J. P. Heritage, and S. J. B. Yoo, "Near Quantum-Limited Single-Shot Full-Field Measurements of Arbitrarily Shaped Optical Waveforms," accepted for publication in *Conference on Lasers and Electro-Optics (CLEO 2009),* Paper CThDD7, 2009.

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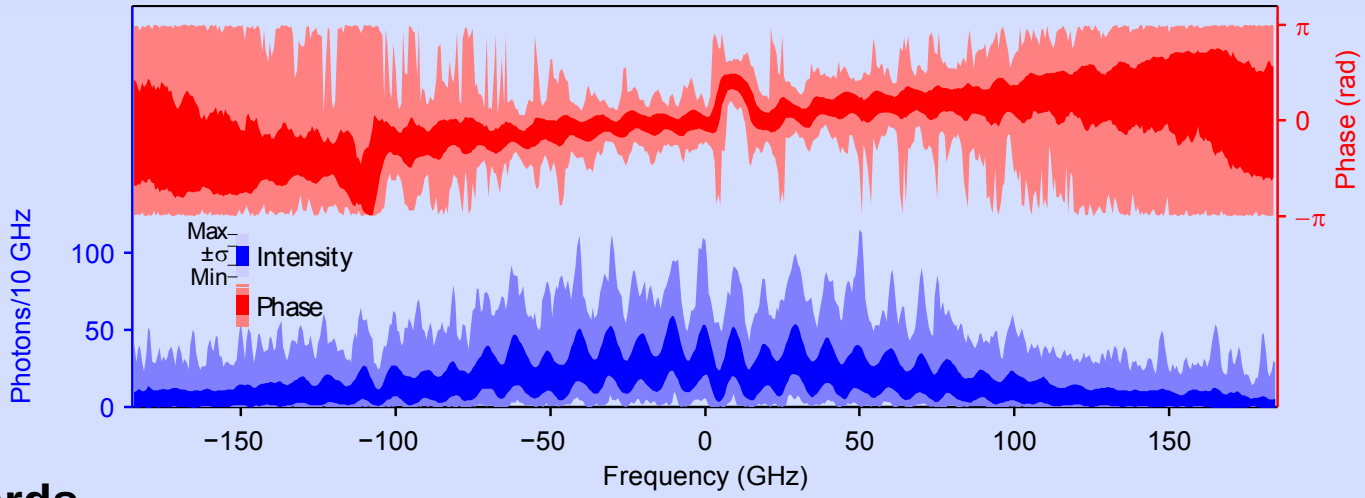
Single-Shot OAWM: 500 photons (64.1 aJ)

Statistics for 200 shots (acquired at 20 Hz)

At least ½ of noise shown is due to shot noise



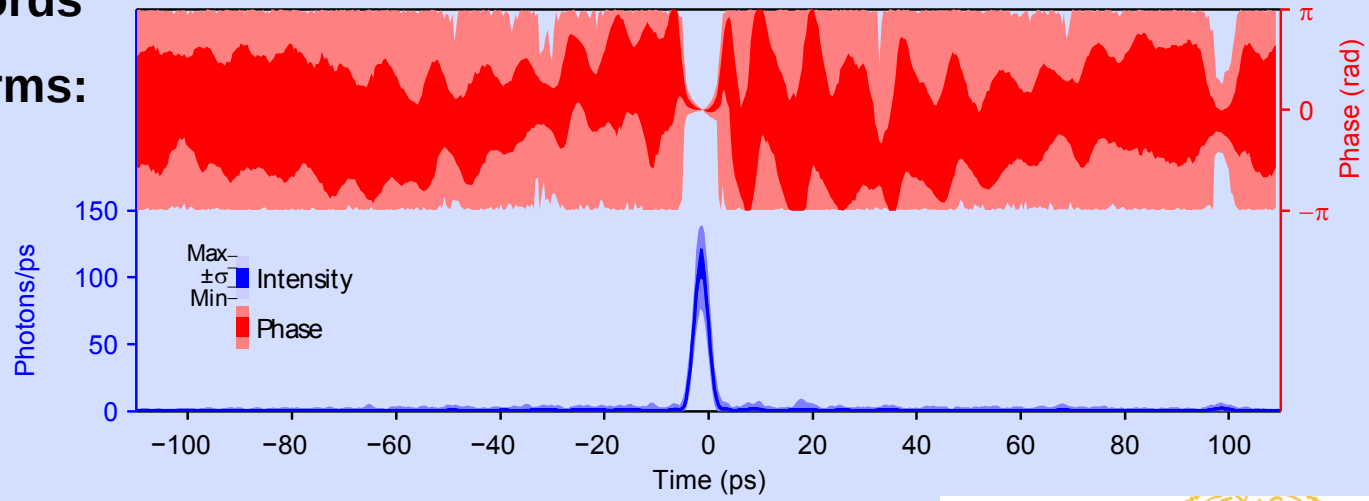
For comparison, records for repetitive waveforms:

Autocorrelation

52 aJ

SHG FROG

124 aJ



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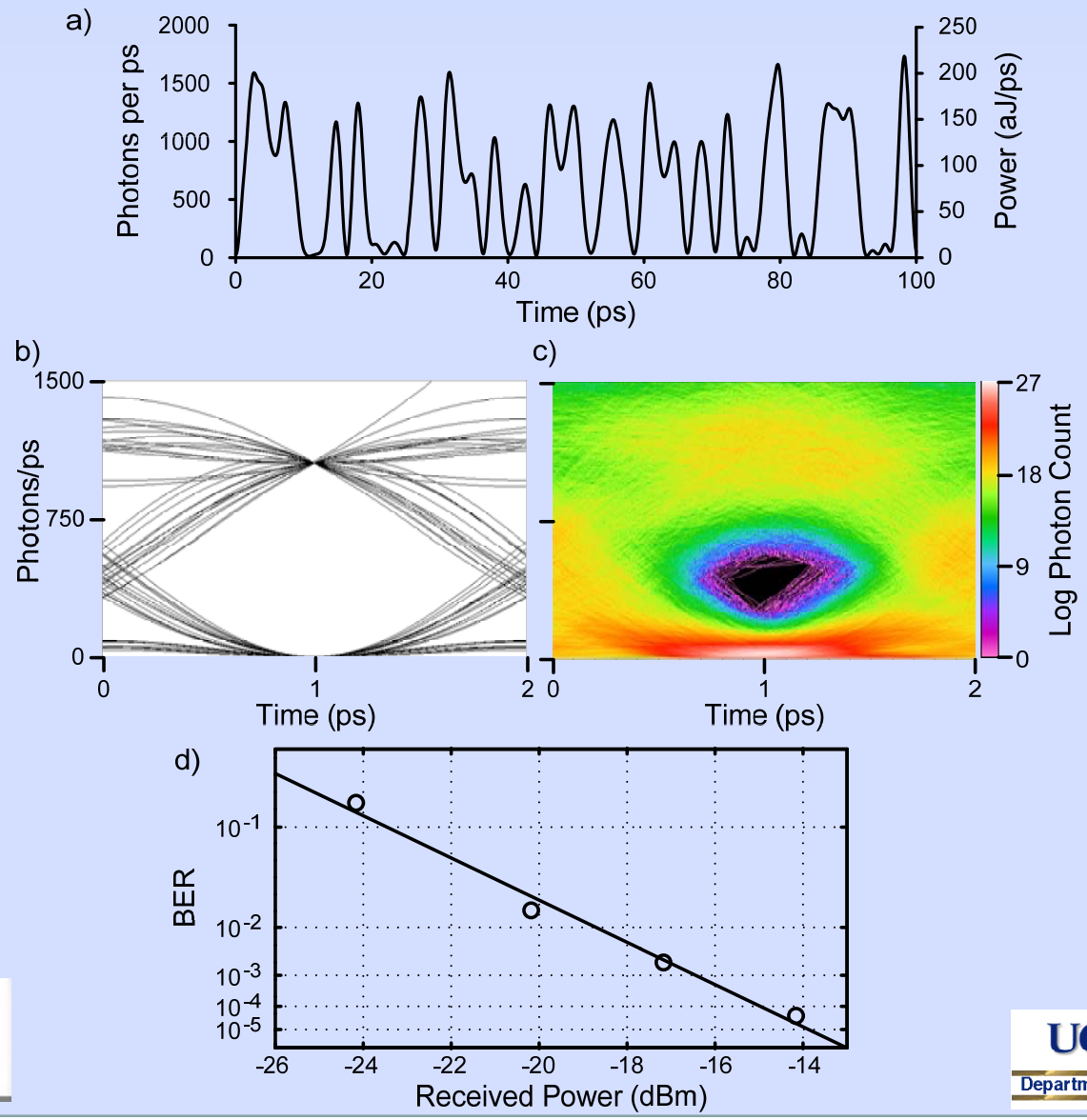
500 Gb/s 50-bit duobinary PRBS measurements using a bandwidth of 490 GHz



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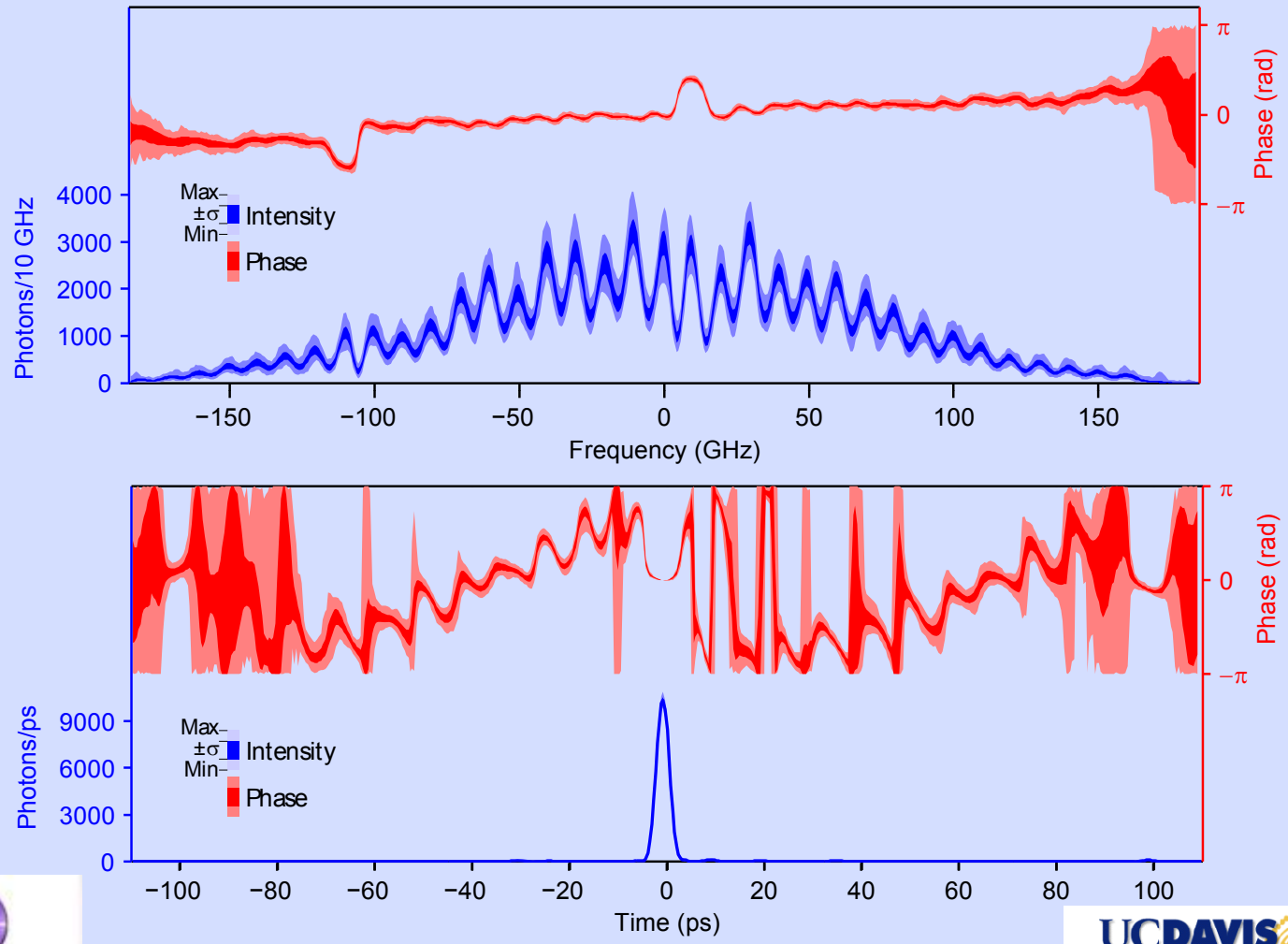
Photonic Integrated Transceivers for Advanced Modulation Formats

- **THz scale Trx and Rcv**
  - Serial modulation schemes will be limited in capacity
  - WDM combination will limit spectral efficiency
  - OAWG/OAWM schemes will allow THz and beyond scaleability with full support of any modulation format of any shape & any multiplexing schemes (e.g. CO-OFDM, CO-WDM, etc)
- **OAWG/OAWM**
  - Energy-efficient low frequency electronics (e.g. 10 GHz)
  - Coherent optical synthesis to scale up to THz and beyond
  - Supports any format/protocol incl. OFDM, CO-OFDM, CO-WDM,
  - Resiliency against failures of modulators or drivers.
  - Monolithic and Hybrid integration possible
  - Benefits from quantum limited detection in amplitude/phase

Single-Shot OAWM: 40,000 photons (5.1 pJ)

Statistics for 200 shots (acquired at 20 Hz)



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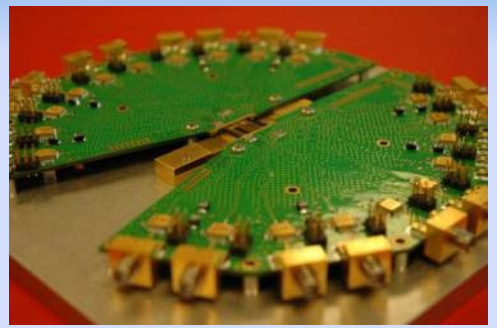
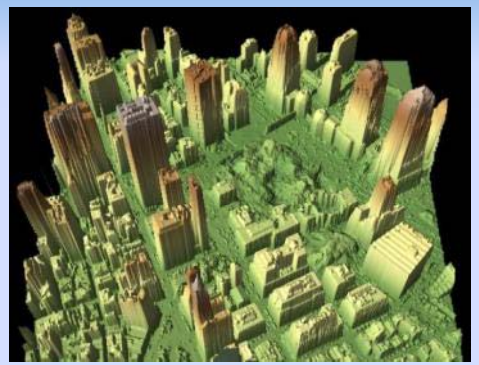
Optical Arbitrary Waveform Generation

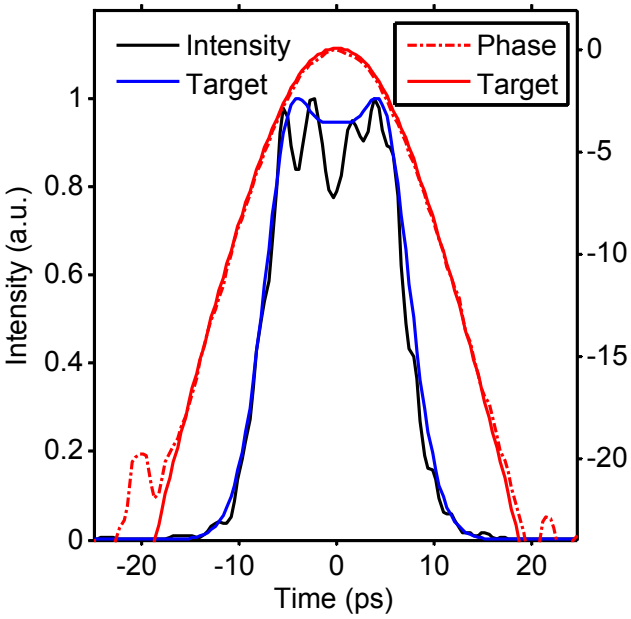


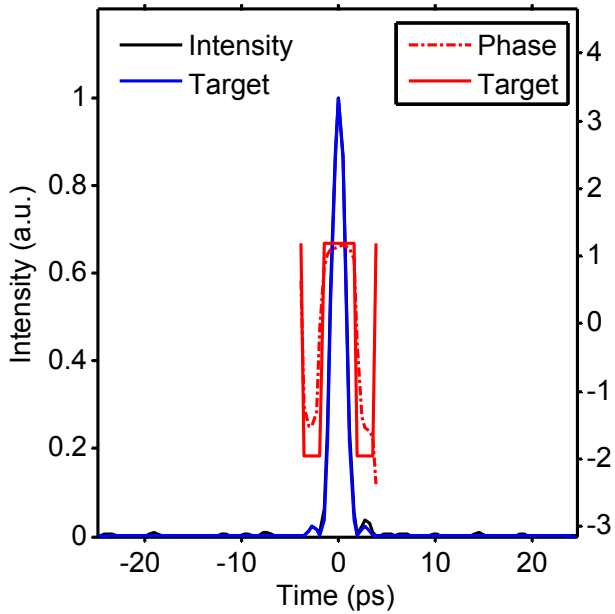
Terascale OAWG

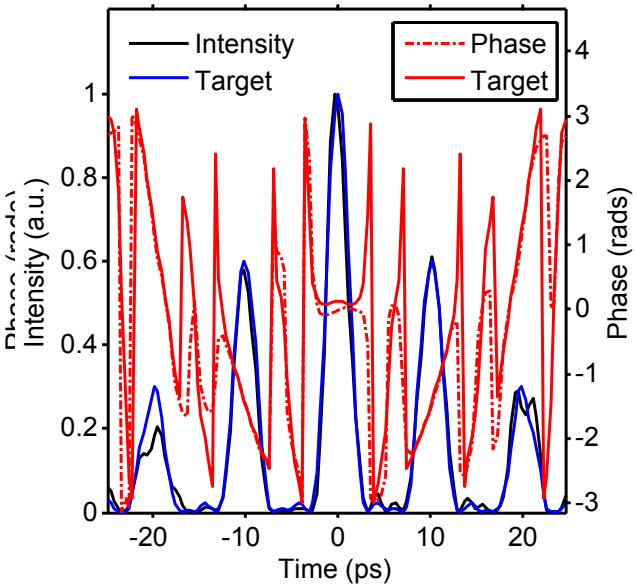


LIDAR applications

~Terabit/sec communication

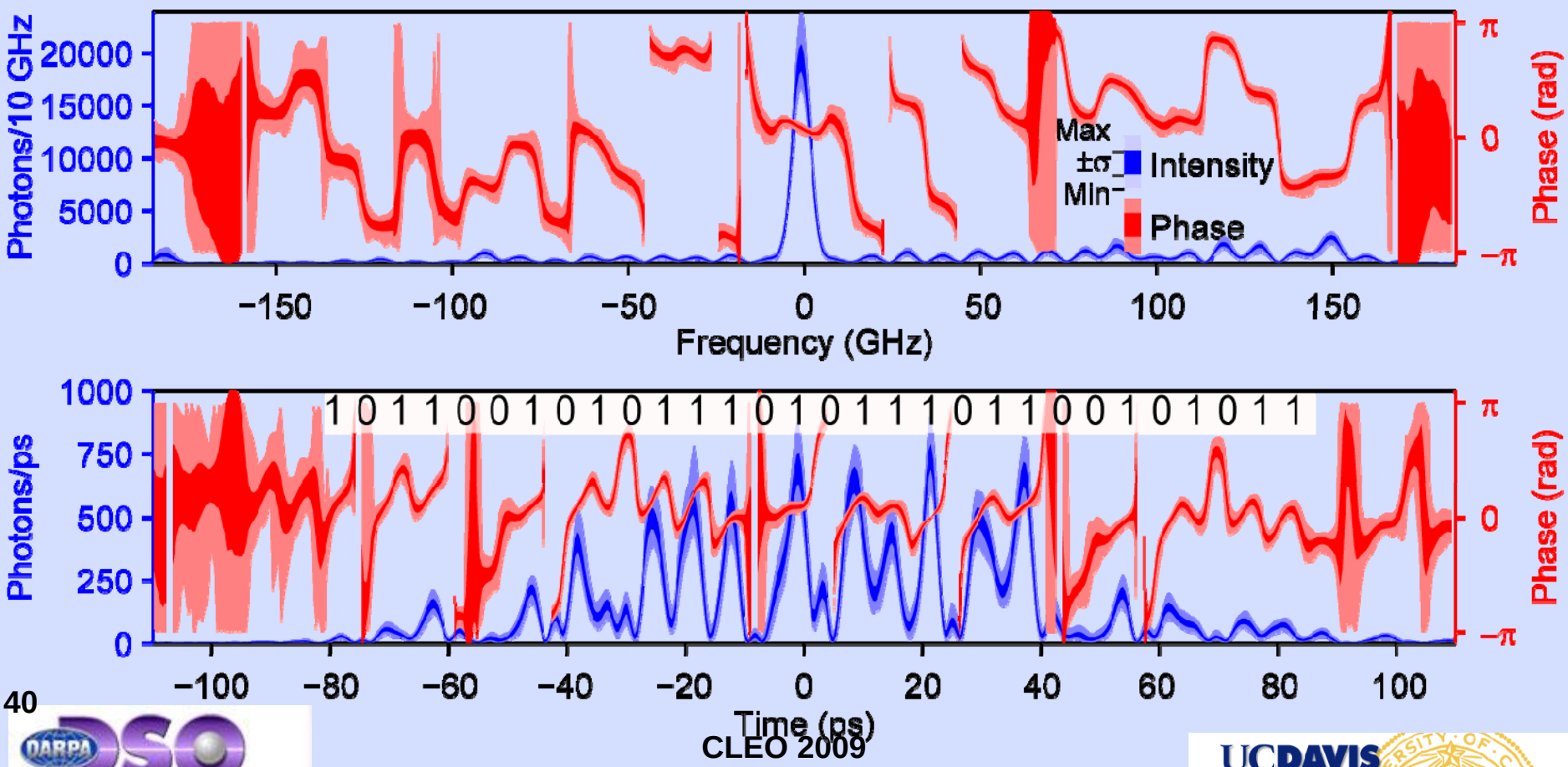






* Super Gaussian is of the form $\exp\left(-\left(\frac{f}{250}\right)^6\right)$

- Correctly retrieves 180 Gb/s bit-sequence with >20 dB variation in spectrum
- Signal spectrum has a strong peak (20,000 photons/10 GHz, f = 0 GHz) which is greater than $R(\omega)$ (9,000 photons/10 GHz), yet weaker than $R(\omega)$ across the rest of the bandwidth (1,000 photons/10 GHz)



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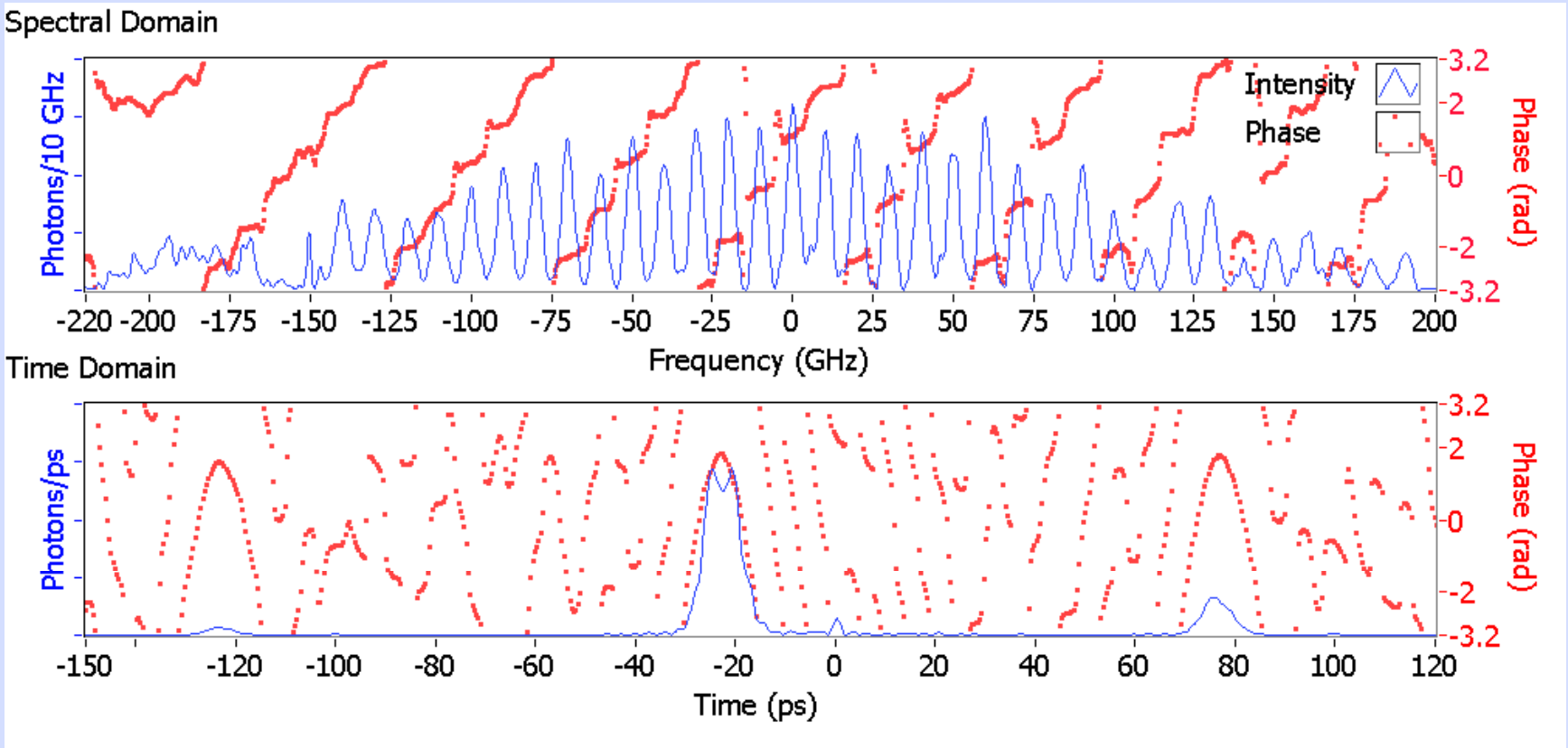
Chirped Pulse Measurement



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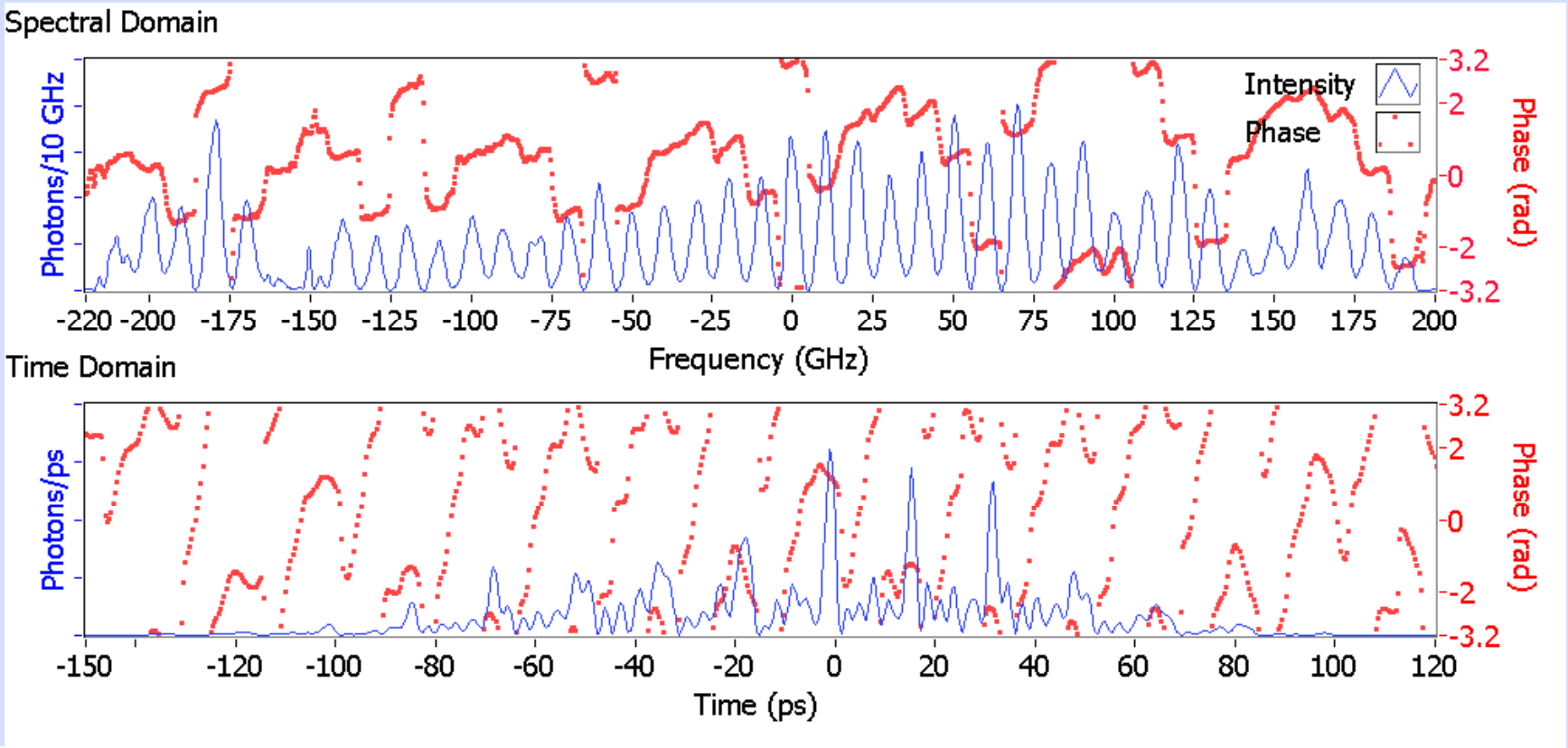
Propagation over 25 km SMF



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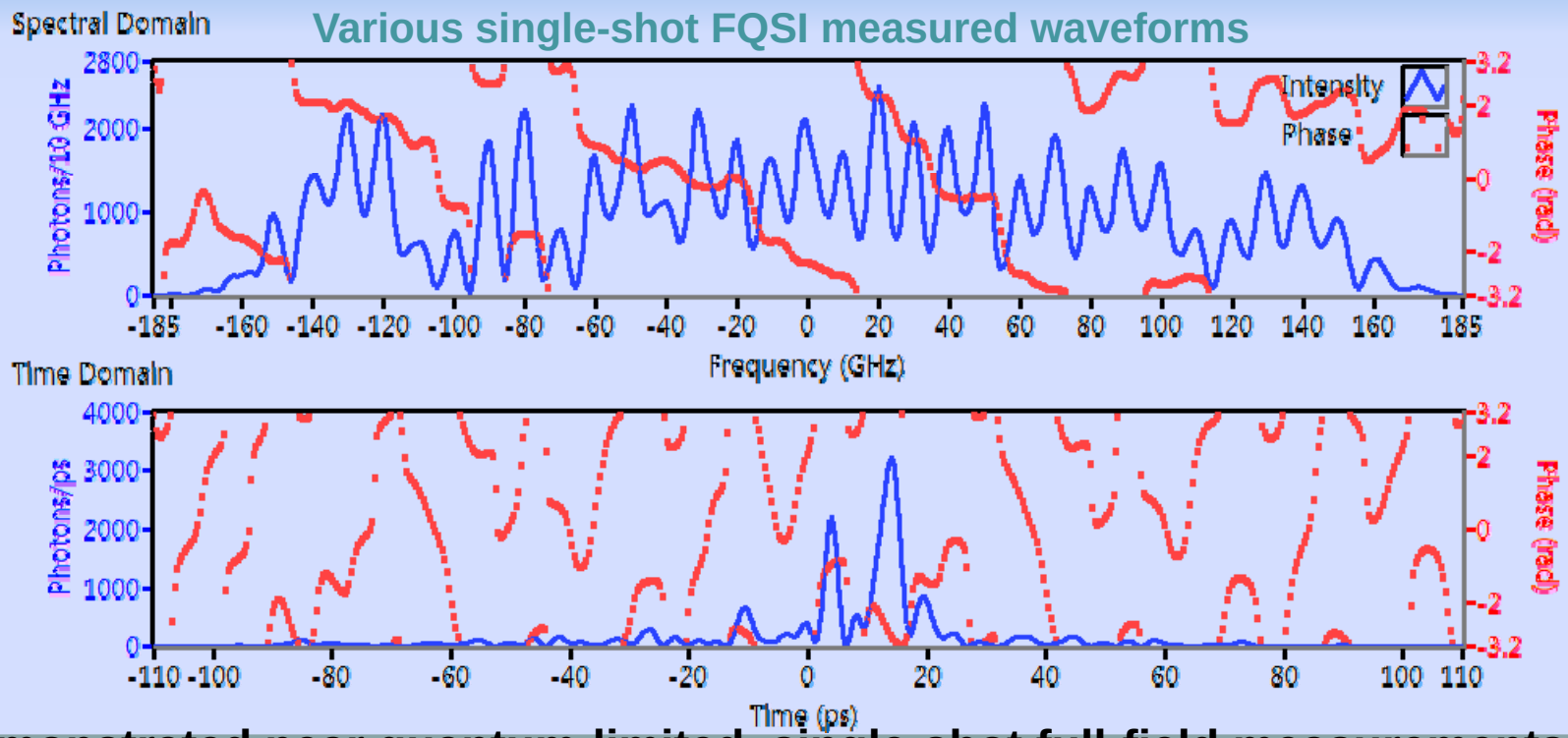
Various Measurements



- **Demonstrated near quantum-limited, single-shot full-field measurements using four-quadrature spectral interferometry (FQSI) with a 20 Hz update rate**
- **500 GHz optical bandwidth (2 ps resolution), 200 ps record length**
- **Single-shot measurements of 150 aJ (1,200 photons) waveforms<**

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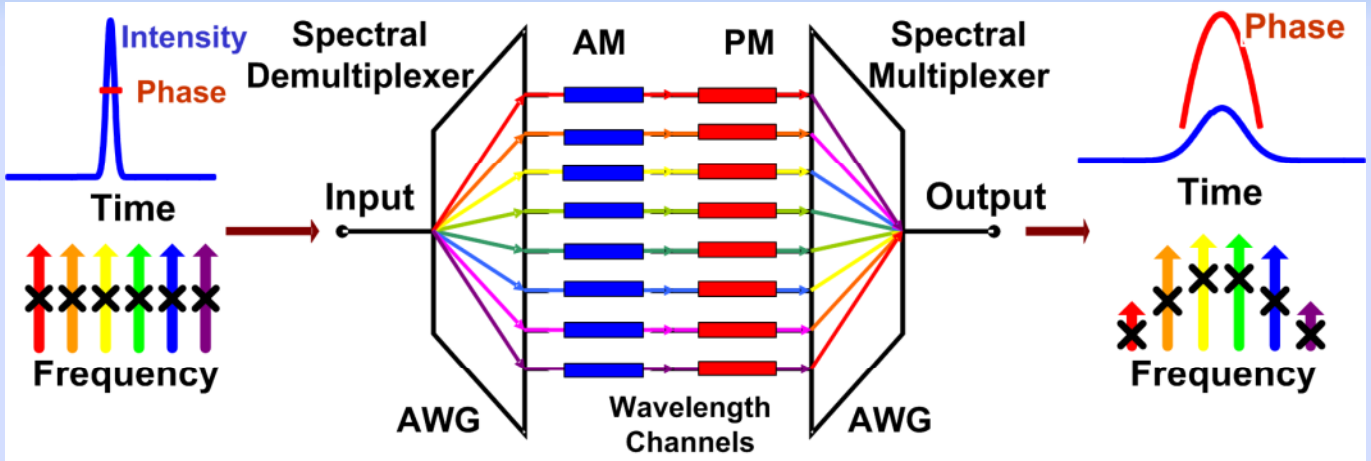
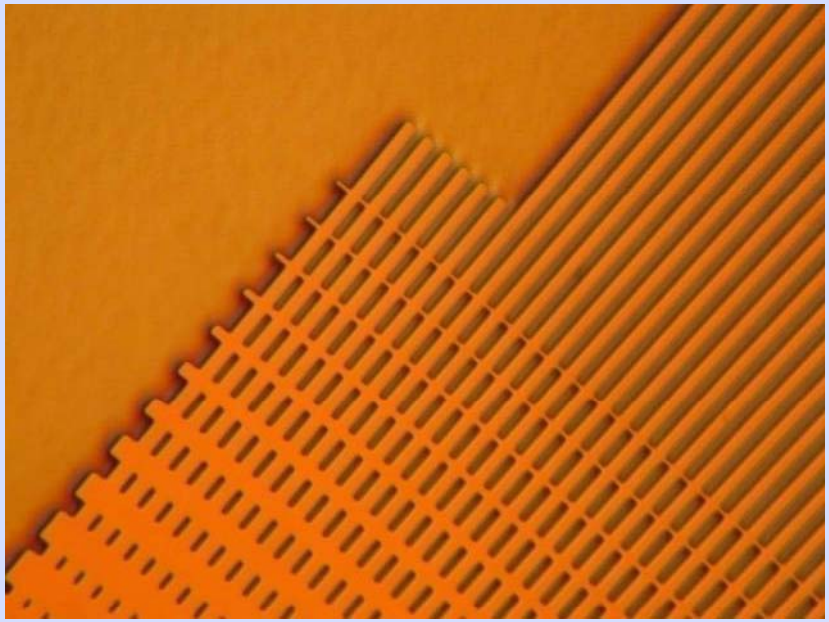
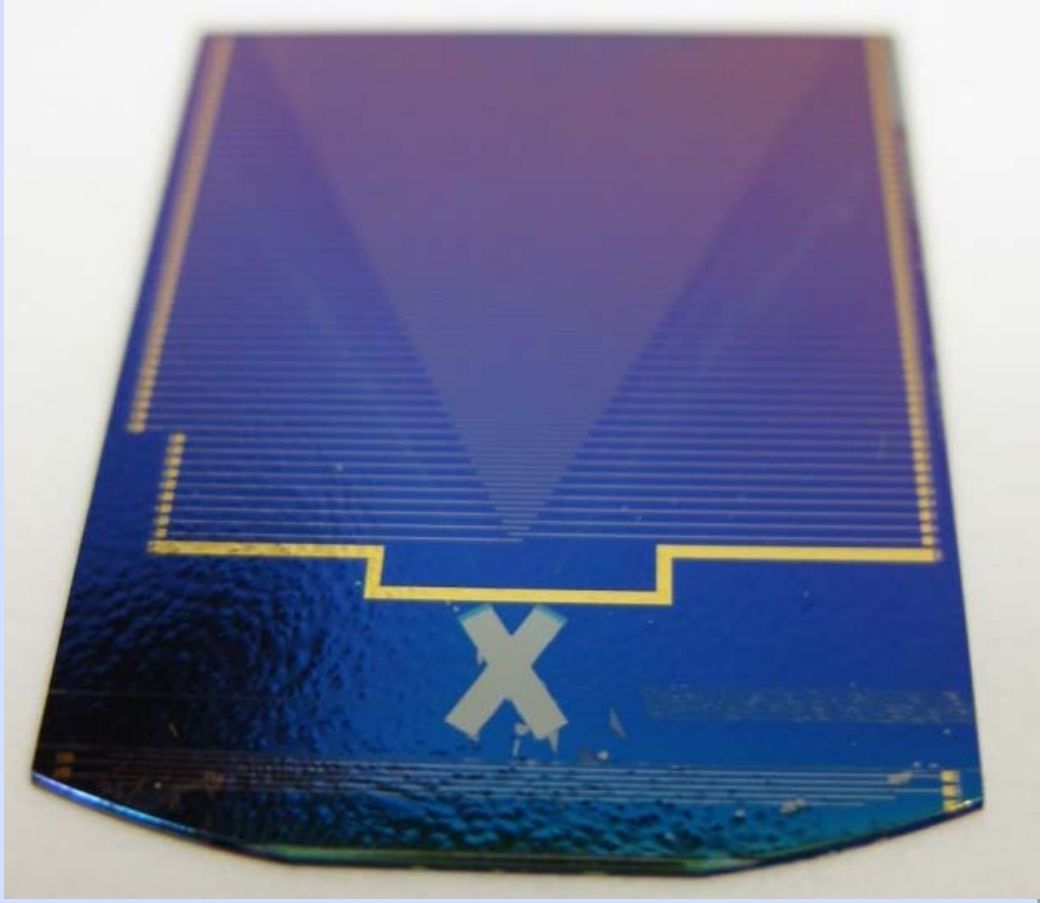
Optical Arbitrary Waveform Generation (OAWG) Encoder



- Fourier Synthesis of Arbitrary Waveforms scaling to Terahertz BW
- Optical arbitrary waveform generation with high-speed modulation
- Tradeoff between wide-optical-bandwidth and electrical-bandwidth
- High-resolution AWGs can offer high-capacity signal processing systems based on low bandwidth electronics (< 10GHz)
- Monolithic InP construction in support of high-speed modulation

Fabricated 5 GHz AWG with segmented tapering





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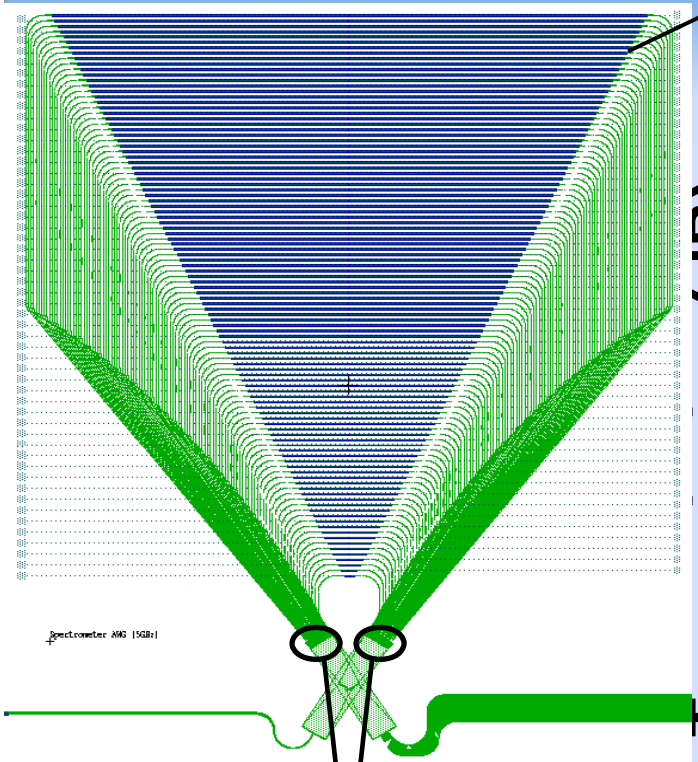
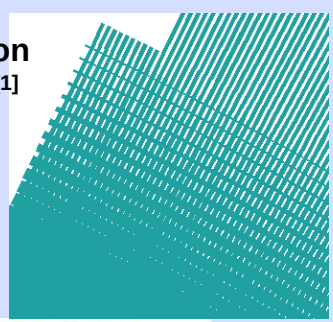
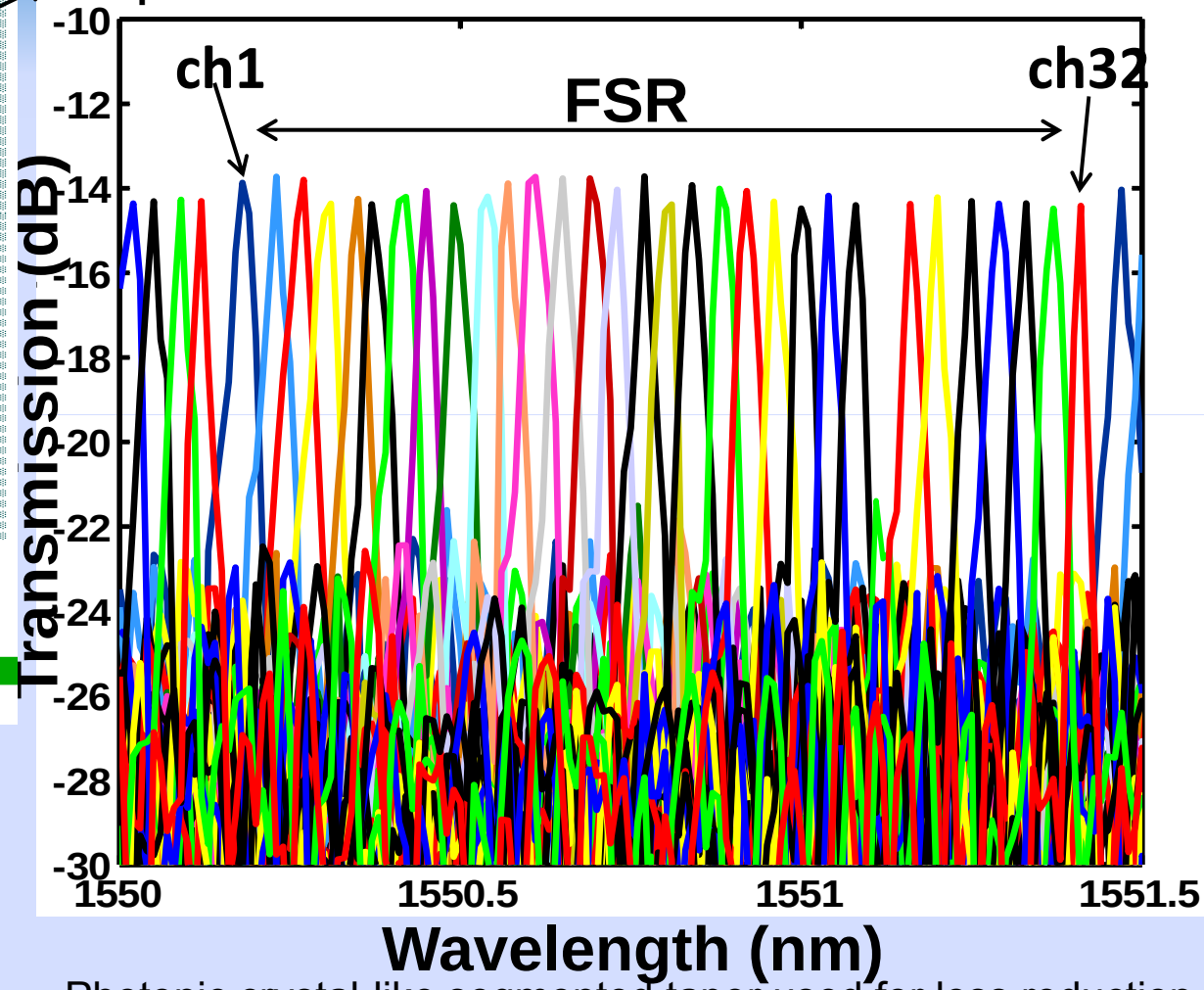
Ultrahigh Density AWG (5 GHz)



EO phase shifters

Segmented transition region[1]





- Photonic crystal-like segmented taper used for loss reduction
- High optical resolution to accommodate lower speed electronic with better power efficiency

[1] Y. P. Li, US Patent No. 5,745,618 (1998).

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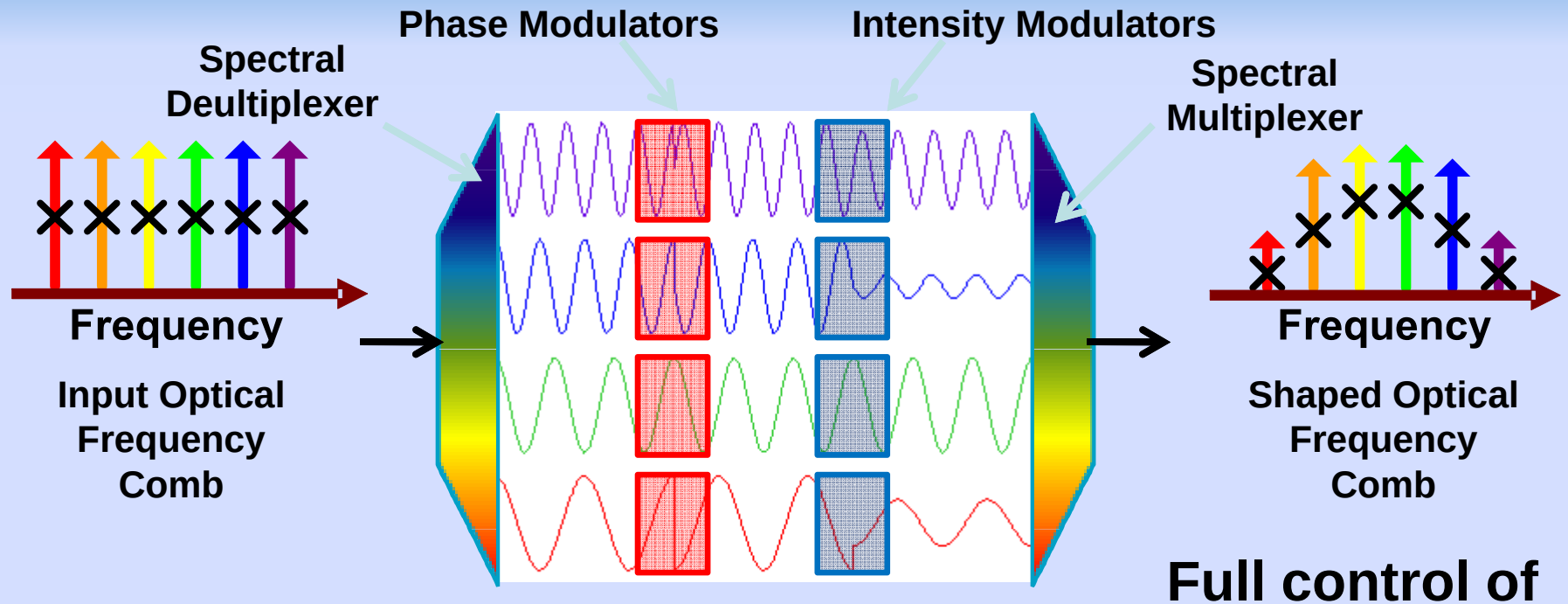
Static OAWG– Integrated Fourier Domain line-by-line Pulse shaping

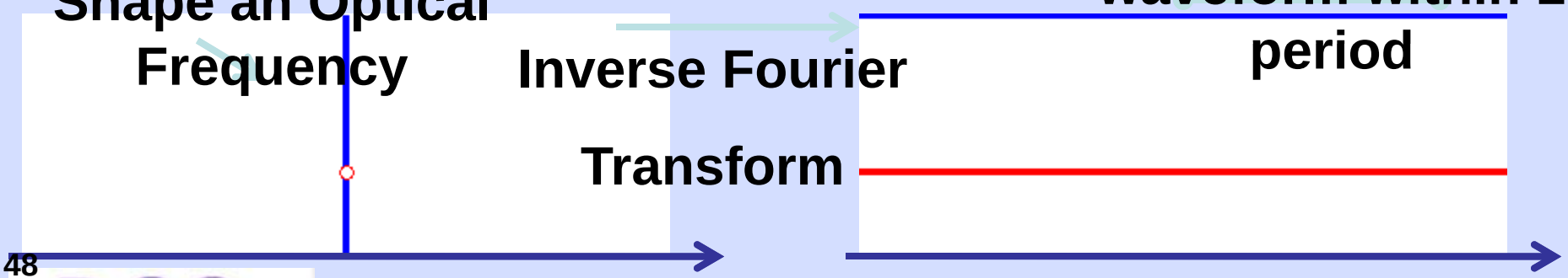
•Static or DC phase and amplitude modulation



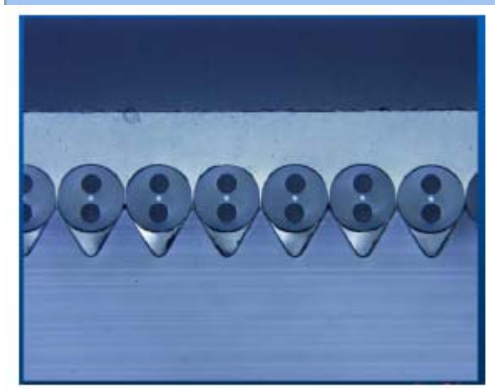
Full control of waveform within 1 period

Shape an Optical Frequency

Inverse Fourier Transform

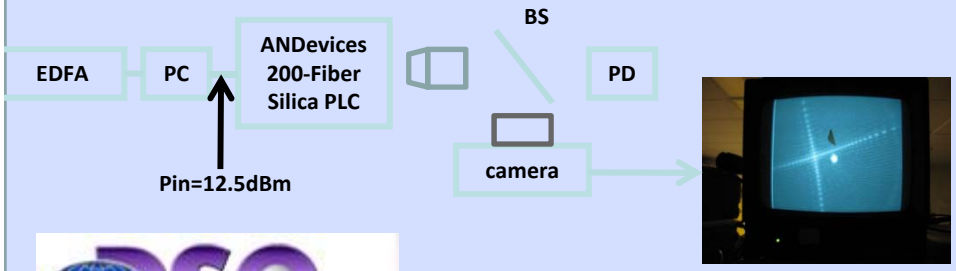


200-Fiber Fan-In Silica PLC



Alligned PM fiber Array on Silicon V-Groove

Channel #	Measured power at PD [dBm]
18	8.2
30	8.1
50	8.4
65	8.0
80	8.0
96	8.1
106	8.0
127	8.2
140	7.9
169	8.2
199	8.5



Average Loss of Fan-In Array= 1.4 dB =12.5dBm (Pin)-8.1dBm (average output)-3dB(from beam splitter)

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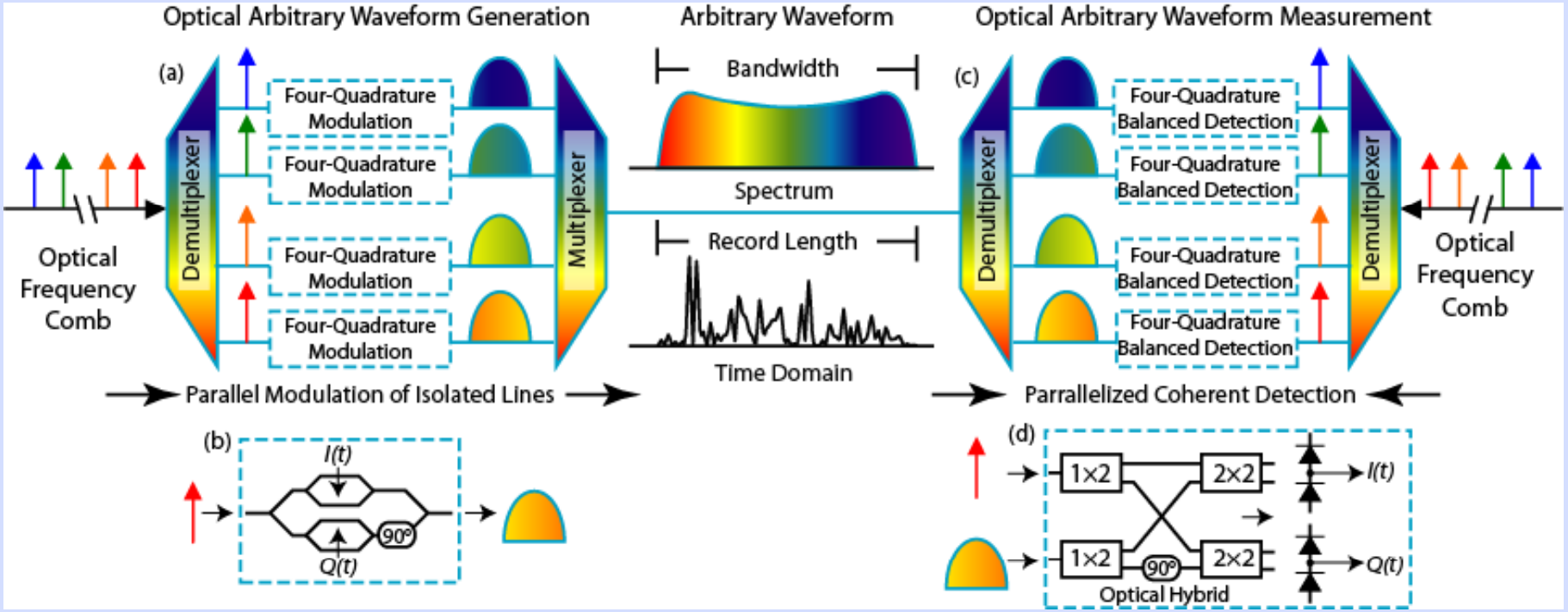
Symmetry in Optical Arbitrary Waveform Generation and Measurement



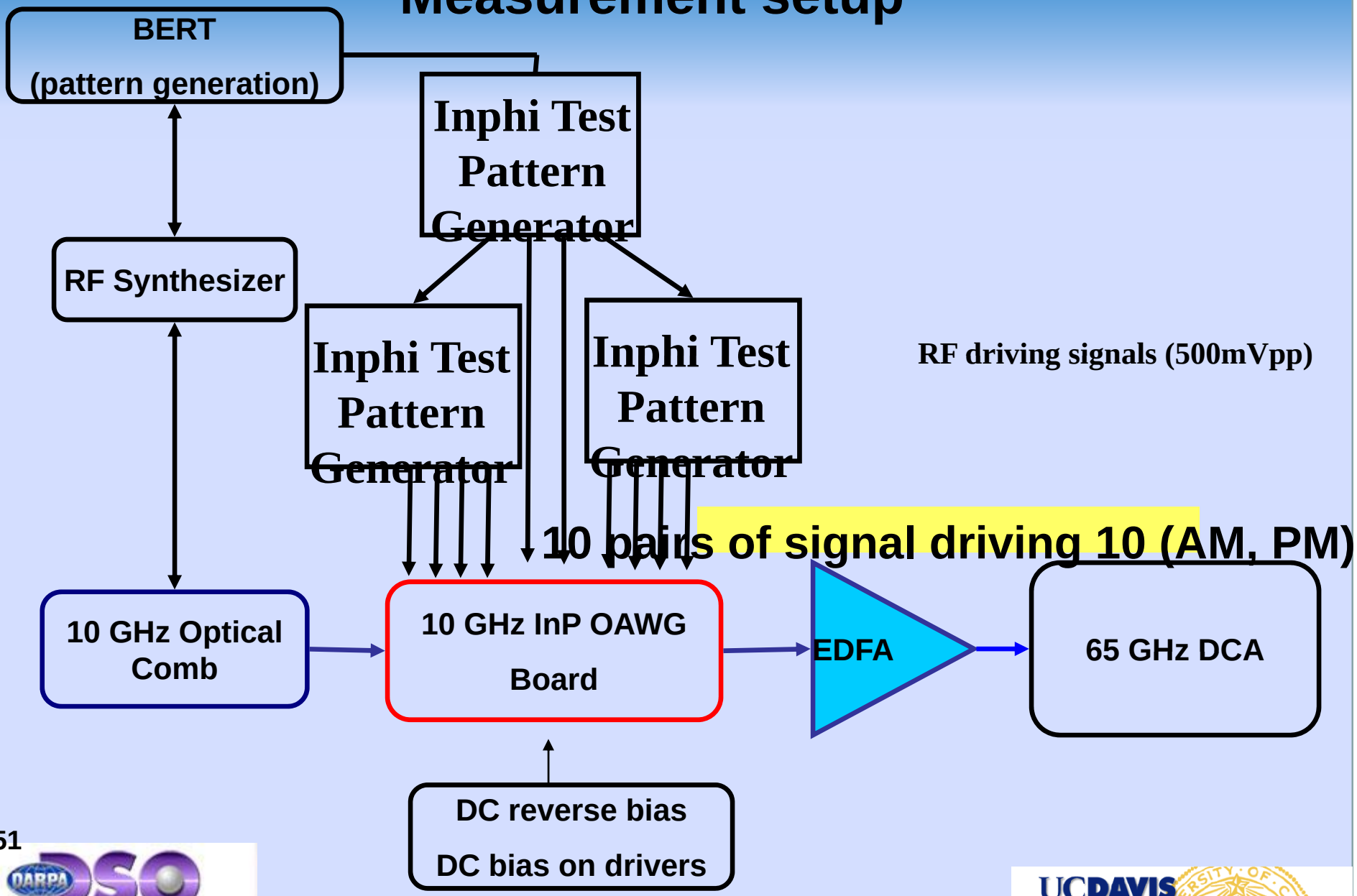
(a) Optical arbitrary waveform generation

(b) Nested Mach-Zehnder modulator for modulating the real and imaginary part (I and Q) of the field

(c) Optical arbitrary waveform measurement

(d) Four-quadrature balanced homodyne coherent detection to measure I and Q

Measurement setup



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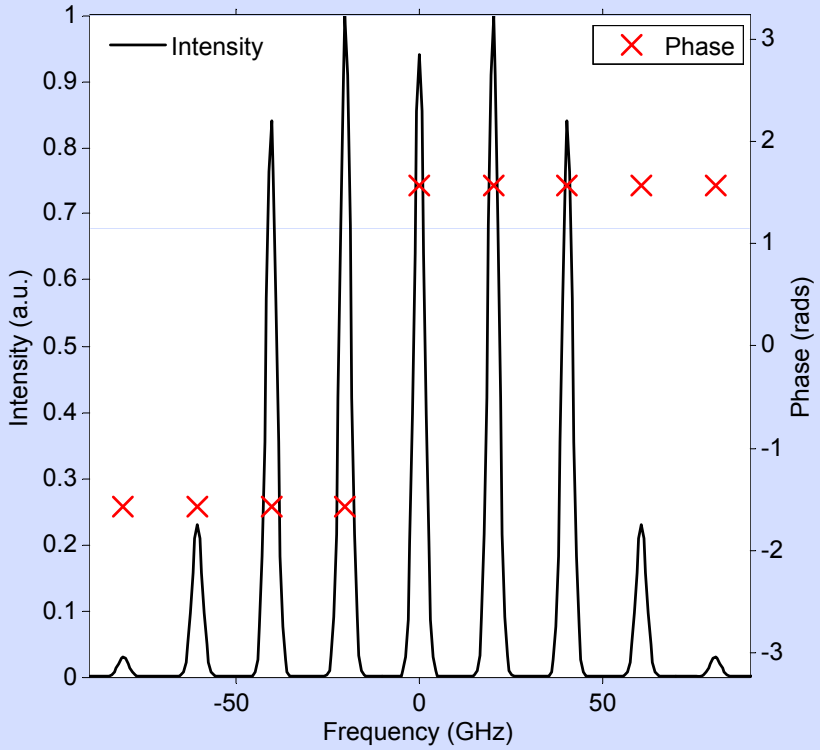
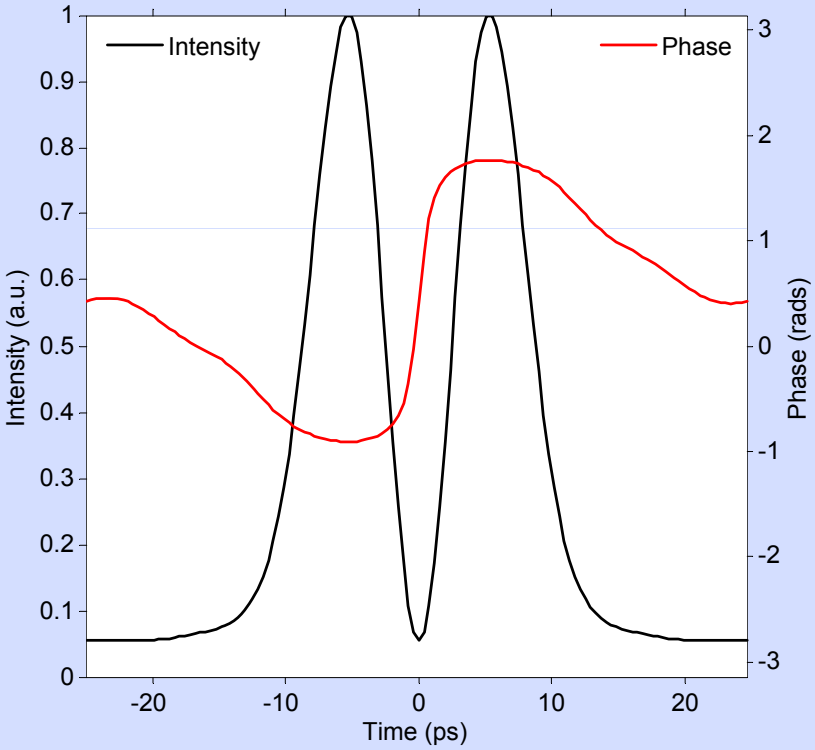
Target Pulse #3
(0-pi Pulse B)





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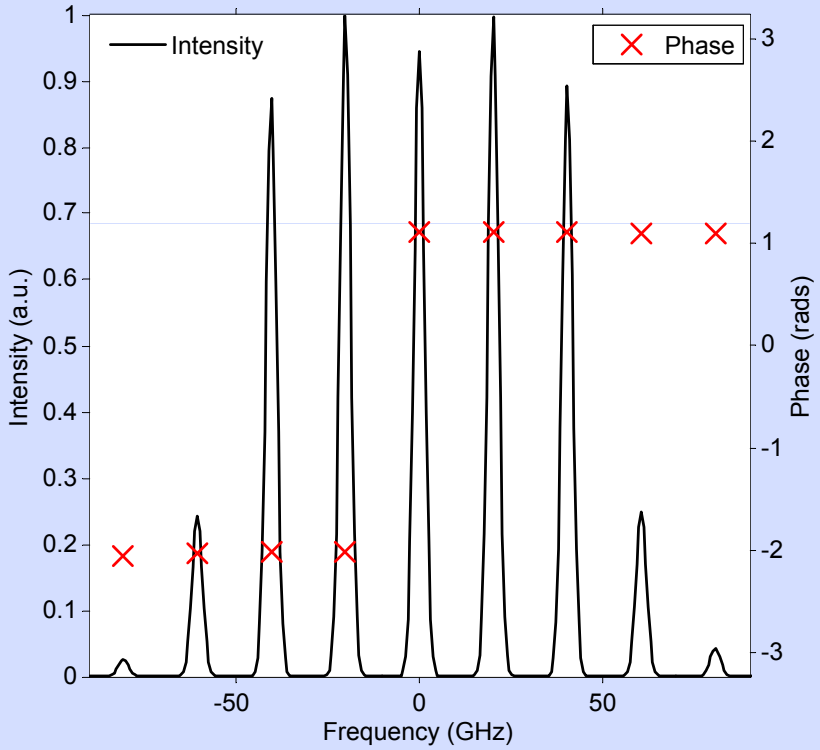
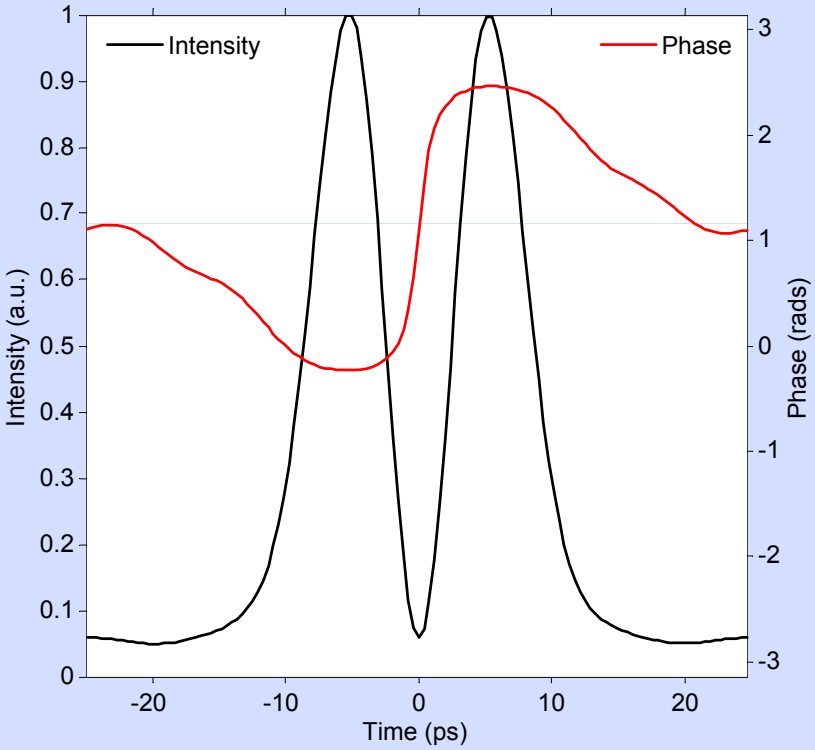
Measured Pulse #3

(0-pi Pulse B)





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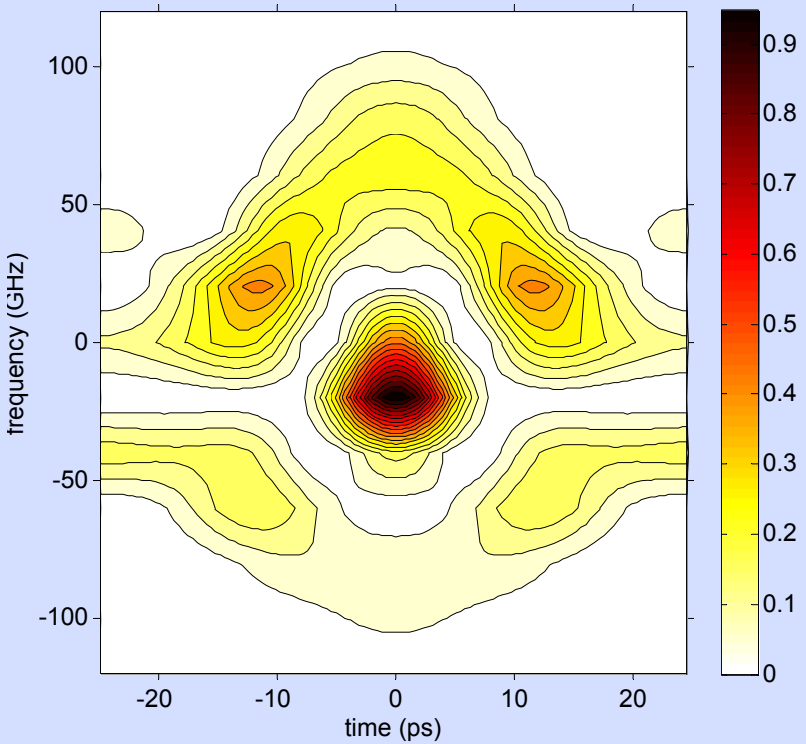
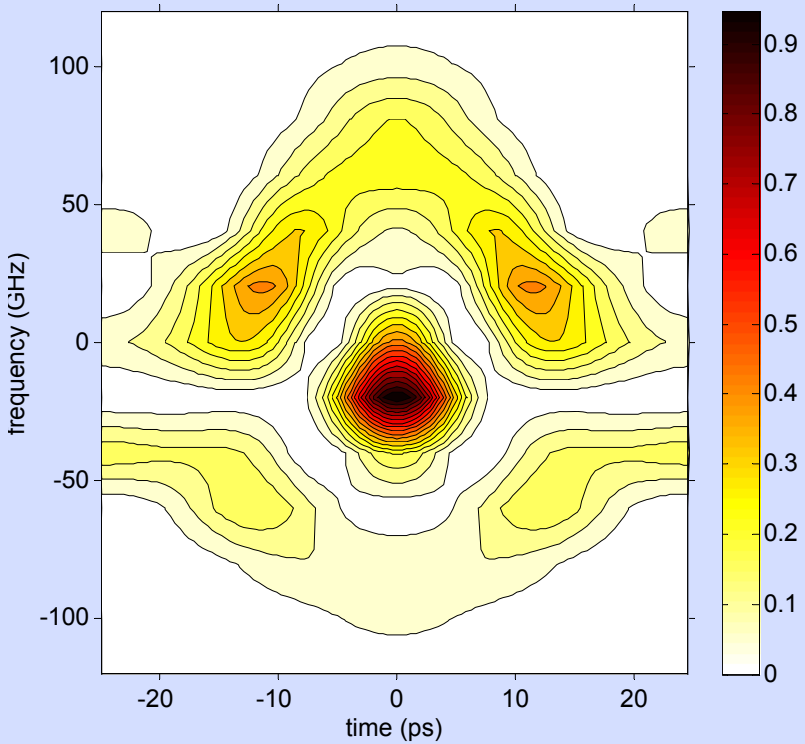
FROG ERROR measurement for Pulse #3

(0-pi Pulse B)

Target



Measured



G = 0.0025

G' = 5%

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OAWM PLC and Fan-In PLC